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APPLICATION NUMBER: ***60/478,308***
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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53 (c).

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☐ *Additional inventors are being named on the _____ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

UNIFORM CAVITATION FOR PARTICLE REMOVAL

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ENCLOSED APPLICATION PARTS *(check all that apply)*

☒ Specification/Claims/Abstract — *Number of Pages* 51

☐ CD(s), Number

☒ Drawing(s) *Number of Sheets* 23

☒ Other (specify) Check for $80.00; Express Mail Certificate and Return-receipt postcard.

☒ Application Data Sheet. See 37 CFR 1.76

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT *(check one)*

☒ Applicant claims small entity status. See 37 CFR 1.27.

☒ A check or money order is enclosed to cover the filing fees

☐ The Commissioner is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number:

☐ Payment by credit card. Form PTO-2038 is attached.

FILING FEE AMOUNT ($)

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

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Respectfully submitted,

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Date 6-12-03

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Docket Number: 7039-005

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

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EXPRESS MAIL CERTIFICATE

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I hereby certify that this paper or fee is being deposited with the United States Postal Service Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to Box Patent Application, Commissioner for Patents, P. O. Box 1450, Alexandria, VA 22313-1450.

Gloria R. Chavarria		June 12, 2003
Name	Signature	Date

1. Check for $80.00
2. Return-receipt postcard
3. Express Mail Certificate (1 p)
4. Provisional Application for Patent Cover Sheet (1 p)
5. Specification (Text/Claims/Abstract) (51 pp)
6. Application Data Sheet (2 pp)
7. Drawing Sheets – 23 (Figs. 1-22B)

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Application Information

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This application is a::	N/A
>Application One:	
Filing Date::	

Prior Foreign Applications:	**NONE**

UNIFORM CAVITATION FOR PARTICLE REMOVAL

Field of the Invention

This invention relates to control of liquid cavitation for particle removal from a surface.

Background of the Invention

One attractive approach for removal of small particles in cleaning processes, such as semiconductor wafer and chip processing, is use of acoustic cavitation in liquids, whereby voids or cavities are created in a liquid and subsequently caused to implode, to undergo micro-acoustic streaming, or to otherwise transfer energy from a cavity to one or more particles adjacent to the (former) cavity. If these (unwanted) particles are located on and temporarily attached to an adjacent surface, such as a semiconductor wafer or chip, these particles can be removed by the force of a collapsing cavity or by micro-acoustic streaming. The frequencies used to induce cavitation in a liquid are often of the order of 1 MHz, and the corresponding cavitation systems are sometimes referred to as megasonic systems.

However, two problems associated with use of cavitation for particle removal with the systems available today are (i) the inhomogeneity of the sizes and density of the cavities or voids created, before collapse occurs, and (ii) the resulting non-uniformity in local particle removal. What is needed is a system that provides and maintains reasonable homogeneity in acoustic cavitation density and that allows a representative cavitation density to be varied according to the nature of the particles to be removed from a surface.

Summary of the Invention

These needs are met by the invention, which provides a system and associated procedure that (i) provides some control over the initial size of the cavities or voids created, (ii) provides reasonable uniformity in the initial cavity sizes and (iii) maintains the size uniformity by batch-to-batch monitoring of the cavities thus created.

The cavities are created, and cavity size is controlled, by use of a cavity creating unit (CCU), including a plurality of closely spaced transducers that produces a corresponding plurality of acoustic cavities as the CCU passes over an adjacent portion of a liquid containing a solid surface from which attached particles are to be removed. Between two consecutive uses of the CCU to remove particles from different batches of surfaces, the CCU is temporarily isolated, and each transducer is separately tested to determine the size and scope of the cavities produced by that transducer. The power and/or excitation signal applied to each transducer is separately adjusted to maintain batch-to-batch uniformity in cavity size and any other parameter(s) relevant to particle removal. By individually testing and adjusting the transducers, batch-to-batch excursions of relevant parameters, such as cavity size, are minimized and uniformity is encouraged or enforced. Single surface treatment and batch treatments are provided.

Brief Description of the Drawings

Figures 1-3, 8-11 and 14 illustrate systems used to practice the invention.

Figures 4A and 4B graphically illustrate increase of measured cavity density with increase in input energy E(f).

Figure 5 illustrates a pre-collapse cavity and its diameter.

Figures 6 and 7 are flow charts of procedures for practicing the invention.

Figure 12 graphically illustrates estimated cavitation density for two transducer configurations.

Figure 13 schematically illustrates use of a shaped (non-planar) transducer on energy deposited in a particle removal liquid.

Figure 15 schematically illustrates batch processing according to an embodiment of the invention.

Figure 16 schematically illustrates an embodiment for delivery and withdrawal of cleaning liquids according to the invention.

Figure 17 graphically shows cavitation activity versus transducer power.

Figure 18 is a photograph illustrating damage to an object surface as a result of application of excessive power to one or more transducers.

Figure 19 illustrates surface angle dithering to randomize acoustic effects.

Figure 20 graphically illustrates increase in cavitation brightness with increase in the number of active adjacent transducers.

Figures 21A, 21B, 21C and 21D are photographs indicating acoustic cavitation wave fields produced with different numbers of transducers activated.

Figures 22A and 22B compare cavitation densities for a transducer array.

Description of Best Modes of the Invention

System 1 is a bottom view of a cavity creating unit (CCU) 11 that may be used to practice the invention. In this embodiment, the CCU 11 includes a polygonally shaped bar (e.g., a triangle, quadrilateral, pentagon or etc.) or curvilinearly shaped bar 13 that includes two or more transducers, 15-i (i = 1, ... , I; I 2), each of which is capable of producing one or more cavities in a liquid in which the transducer is immersed. The transducers 15-i are individually driven by an energy source 17 so that the energy delivered to each transducer can be individually adjusted. Preferably, the energy source 17 includes a control mechanism that permits adjustment of (i) the energy delivered per unit time to each transducer 15-i and (ii) the frequency at which each transducer is driven. Preferably, the energy source 17 can provide two or more distinct drive frequencies for each transducer 15-i.

The CCU 11 is part of an assembly 21, shown in a top view in Figure 2, that includes: the CCU 11 and transducers (not shown in Figure 2); a liquid container 23 that is partly or wholly open at the top; a selected liquid 25 within the container; one or more surfaces 27, immersed in the liquid, from which one or more attached particles are to be removed; a CCU re-orientation mechanism 29 that (i) positions the CCU 11 over the liquid 25 in a first position P1 and (ii) rotates the CCU 11 to a second position P2 that is spaced apart from the container 23 and the liquid 25, for transducer testing and adjustment; and a container rotation mechanism 31 that causes the container 23 to rotate at a selected angular velocity ω about a selected vertical axis V-V, preferably a vertical axis that passes through a center of the container.

In the second position P2, the CCU bar 13 is immersed in a second container 33 of a second selected liquid 26 (preferably, but not necessarily, the same as the first liquid 25) for individual or group testing of action of the transducers 15-i (Figure 1), as discussed in the following in connection with Figure 3.

Figure 3 is a sectional side view of a transducer test assembly 40, one of a group of two or more such assemblies, that can be used as part of the CCU shown in Figures 1 and/or 2. The transducer assembly 16 includes a CCU housing 41, which may be a hollow cylinder having a lateral housing extension 43 and having a thin diaphragm 45 (thickness h1 $\approx$ 0.1 - 1 mm) that supports a transducer 15-i that vibrates with a selected output energy E(f) at one or more selected output frequencies, $f = f_n$, in a range 100 - 3000 KHz. In the second position P2, the transducer 15-i is electrically connected to a servo control module 47 that adjusts one or more of (1) the output energy E(f) and (2) the output frequency, $f = f_n$, in response to receipt of a selected feedback signal at the servo control module 47. The servo control unit 47 is connected to an image processing module 49, which receives signals from an ICCD image forming module 51. In a CCU monitoring mode, the diaphragm 45 and a small portion of the bottom of the housing 41 are immersed in a small thickness h2 of the second liquid 26, where the liquid thickness h2 $\cong$ 0.1 - 5 mm.

The ICCD module 51 is positioned so that an ICCD sensor 53 faces the diaphragm 45 and transducer 15-i (Figure 1) and forms an image of one or more acoustic cavities produced in the liquid L when the transducer 15-i is activated. The ICCD sensor 53 primarily measures or otherwise senses a volume density ρ(cav) of acoustic cavities, which can vary linearly or nonlinearly with the energy input E(f) at an input frequency f. The maximum diameter of a pre-collapsed cavity produced by a transducer 15-i will decrease monotonically with an increase in input frequency, $f = f_n$, and will depend upon relevant characteristics of the liquid, such as wave propagation velocity in the liquid and surface tension of the liquid. Variation of the input frequency, $f = f_n$, can indirectly cause a variation in

the volume density ρ(cav), for example, by decreasing the volume density as the maximum pre-collapse diameter increases.

Figures 4A and 4B graphically display measurements by a sensor, across a field of two adjacent transducers (separation distance = 0.5 - 5 cm), of acoustic cavities produced with an input frequency, $f = f_n = 1$ MHz, for input energies corresponding to (1) 40 volts and 40 volts (Figure 4A) and (2) 40 volts and 20 volts (Figure 4B). The maximum cavity densities for 40 volts is approximately 7 times as large as the cavity volume density for 20 volts. For this experiment, the cavity density appears to increase nonlinearly with increase in input energy E(f).

Figure 5 illustrates a cavity C, produced by an activated transducer and having a pre-collapse diameter d_{cav} (before cavity collapse) that is partly or fully determined by the output frequency f_n and by one or more parameters of the liquid 26. Ideally, each cavity C produced by each transducer 15-i has a pre-collapse cavity diameter d_{cav} with precisely the same, or substantially the same, value (e.g., 25 μm). A preferred range of transducer output frequencies f_n is 100 - 3,000 KHz, which can generate pre-collapse cavity diameters d_{cav} in a range 0.1 - 1 mm.

In practice, an average cavity density ρ(cav) produced by a given transducer 15-i (Figure 1) will vary with time as the transducer ages, and because of several environmental factors, and transducer-to-transducer variation will occur as well. The system shown in Figure 3 tests each transducer 15-i, when the CCU bar 13 is in the second position, to determine an average density ρ(cav;i) of cavities presently produced by this transducer and compares this density with a reference or "ideal" cavity density ρ(cav;ref). If the magnitude of the difference, |ρ(cav;i) - ρ(cav;ref)| is greater than a selected non-negative threshold value $\Delta\rho_{thr}$ (which may be 0), the energy output E(f) and/or the output frequency, $f = f_n$, is adjusted (separately, for each transducer) to reduce the difference magnitude to no more than $\Delta\rho_{thr}$, or to minimize the difference magnitude if this magnitude cannot be reduced to no greater than $\Delta\rho_{thr}$. After each transducer 15-i has been tested and the input energy E(f) and/or the input frequency, $f = f_n$, for each transducer has been adjusted accordingly, the CCU 11 and associated transducers 15-i are moved

to the first position P1 in Figure 3, and one or more surfaces 27, immersed in the first liquid 25, is cleaned. Preferably, the individual transducers 15-i (Figure 1) are retested and adjusted before each surface 27 is cleaned. The time required for testing and adjustment may vary from about 15 sec to about 45 sec, or greater if desired.

As a first alternative, this testing and adjustment procedure may be performed after N surfaces 27 have been cleaned, where N is a selected integer greater than 1. As a second alternative, this testing and adjustment procedure may be performed on a randomly chosen subset of all the transducers 15-i'; and if each transducer 15-i' in this subset satisfies $|\rho(cav;i') - \rho(cav;ref)| \le \Delta\rho_{thr}$, the testing and adjustment procedure is terminated and the CCU 11 and associated transducers are returned to the first position P1 for surface cleaning.

Figure 6 is a flow chart of a procedure for practicing the invention. In step 61, a CCU, including two or more transducers, is received into a testing basin (e.g., the container 33 in Figure 2) containing a selected test liquid. In step 63, a counting index i, having a range $i = 1, \ldots, I$, where I (≥ 2) is the number of transducers on the transducer bar, is initialized (e.g., $i = 1$). In step 65, transducer number i is activated, and one or more pre-collapse cavities is formed in the test liquid. In step 67, a representative cavity density $\rho(cav)$ is estimated, preferably using an imaging mechanism such as the ICCD module 51 in Figure 3. In step 69, a magnitude of a density difference $\Delta\rho(i) = |\rho(cav;i) - \rho(cav;ref)|$ is computed and compared with a selected non-negative threshold density difference $\Delta\rho_{thr}$. In step 71, the system determines if $\Delta\rho(i) \le \Delta\rho_{thr}$. If the answer to the query in step 71 is "yes," the system moves to step 73 and determines if the counting index satisfies $i \ge I$. If the answer to the query in step 73 is "yes," the system optionally moves the CCU out of the test liquid, moves or re-orients the CCU, immerses the CCU in a particle removal liquid, and uses all transducers, as adjusted, to generate two or more cavities in the particle removal liquid, in step 75.

If the answer to the query in step 73 is "no," the system increments i ($i \rightarrow i+1$) and returns to step 65, and steps 65 through 71 are repeated at least once. If

the answer to the query in step 71 is "no," in step 77 the system varies at least one of (i) an output energy E(f) associated with the transducer number i and (ii) an output frequency, $f = f_n$, of the transducer number i, until at least one of the following two conditions is satisfied: (1) the density difference $\Delta\rho(i) = |\rho(cav;i) - \rho(cav;ref)|$ is reduced to a value no greater than the threshold difference $\Delta\rho_{thr}$ and (2) the density difference $\Delta\rho(i) = |\rho(cav;i) - \rho(cav;ref)|$ is minimized. The system then moves to step 73.

Figure 7 is a flow chart of an alternative procedure for practicing the invention. Steps 81, 83, 85 and 87 correspond to the respective steps 61, 63, 65 and 67. In step 89, a subset, having a selected number I' of members (numbered i' = 1, ... , I', with $1 \leq I' < I$), of the set of I transducers is randomly chosen.

In step 91, a cavitation density difference $\Delta\rho(i') = |\rho(cav;i') - \rho(cav;ref)|$ is computed, for i' = 1, ... , I', and a representative average $D(\Delta\rho(1'), \ldots, \Delta\rho(I'))$ is computed, depending upon one or more of the difference values $\Delta\rho(i')$. In step 93, the system determines if $D(\Delta\rho(1'), \ldots, \Delta\rho(I'))$ is greater than the selected threshold difference $\Delta\rho_{thr}$.

For example, the representative average D may be a weighted linear or nonlinear average, such as

$$D(\Delta\rho(1'), \ldots, \Delta\rho(I')) = \{\sum_{i'=1}^{I'} w(i')\cdot\{\Delta\rho(i')\}^p\}^{1/p}, \tag{1}$$

where p is a selected positive number and w(i') are non-negative weighting coefficients satisfying

$$\sum_{i'=1}^{I'} w(i') = 1. \tag{2}$$

The quantity $D(\Delta\rho(1'), \ldots, \Delta\rho(I'))$ represents an average of the difference magnitudes for the randomly chosen subset of I' transducers. If one allows the exponent p to increase without limit and assumes that $w(i') > 0$ for all indices i' in the subset, for very large values of p, the quantity D in Eq. (1) approaches

$$D(\Delta\rho(1'), \ldots, \Delta\rho(I')) \cong \Delta\rho(i';\max) = \max\{\Delta\rho(1'), \ldots, \Delta\rho(I')\}. \quad (3)$$

Thus, for very large values of the exponent p, the quantity $D(\Delta\rho(1'), \ldots, \Delta\rho(I'))$ is approximately the largest value among the difference magnitudes, and this number is compared with the threshold difference $\Delta\rho_{thr}$. In this limit, the maximum magnitude difference $\Delta\rho(i';\max)$ is compared with the selected threshold difference $\Delta\rho_{thr}$. For lower values of the exponent p, the quantity $D(\Delta\rho(1'), \ldots, \Delta\rho(I'))$ provides other averages. For example, with the choice $p = 1$, the representative average $D(\Delta\rho(1'), \ldots, \Delta\rho(I'))$ becomes a conventional weighted average of the density differences $\Delta\rho(i')$. With the choice $p = 2$, the representative average $D(\Delta\rho(1'), \ldots, \Delta\rho(I'))$ becomes a weighted means square average of the density differences $\Delta\rho(i')$.

If the answer to the query in step 93 is "yes," the system terminates the transducer testing process and uses collection of transducers 15-i' ($i' = 1, \ldots, I'$) as is, in step 95, and optionally moves the CCU bar out of the test liquid, moves or re-orients the CCU bar, immerses the CCU bar in a particle removal liquid, and uses all transducers, as adjusted, to generate two or more acoustic cavities in the particle removal liquid, in step 97. If the answer to the query in step 95 is "no," the system reverts to the procedure beginning at step 63 in Figure 5, in step 99.

The test liquid and the particle removal liquid may be the same or may be different in one or both of the procedures in Figures 6 and 7. Suitable particle removal liquids include DI water, ammonia (NH_3), hydrogen peroxide (H_2O_2), sulfuric acid (H_2SO_4), and ozone (O_3) in DI water.

The preceding development is appropriate for surface cleaning of one or a few surfaces, such as semiconductor surfaces, at about the same time. Figure 8 schematically illustrates a system 100 for cleaning a batch of two or more surfaces, 101-j, numbered $j = 1, \ldots, J$ ($J \geq 2$), preferably surfaces that are substantially planar. The surfaces 101-j are oriented approximately parallel to each other in a container or tank 103, having an open upper surface and containing a sufficient amount of a selected particle removal liquid 105 to fully immerse each surface,

and the removal liquid extends to a thin diaphragm 109 (thickness h3 $\cong$ 0.1 - 1 mm).

Above the diaphragm 109, a test liquid 111 (which may be, but is not necessarily, the same as the particle removal liquid 105) is provided in each of a sequence of test cells 113-i (i = 1, ... , I; I $\geq$ 2) that are contiguous to the diaphragm 109 as shown. Test liquid 111 for the test cells 113-i is fed through a labyrinthine liquid ingress system 115 that permits the liquid to pass but does not permit any light generated extraneous to the cells to enter the cells. That is, the cells 113-i are preferably light-proof. A noble gas (e.g., Ar, Ne, Kr or Xe), preferably at or near saturation concentration, is included in the test liquid 111 (e.g., DI water) to promote or encourage sonoluminescent discharge within the cells 113-i in response to receipt of energy waves (from the diaphragm 109) generated by acoustic cavitation on the removal liquid 105.

The assembly of test cells 113-i is covered by a light-proof hood 117 having an apex including an ICCD module 119 that forms a plurality of images of the sonoluminescent response of the test liquid to determine if each transducer is functioning within a permitted range. The sonoluminescent field produced at a given location above the diaphragm 109 and sensed by the ICCD module 119 reflects the acoustic field produced in the removal liquid at a corresponding location below the diaphragm 109.

Acoustic cavitation in the removal liquid 105 is generated by K transducers 121-k, numbered k = 1, ... , K (K $\geq$ 2) that are positioned on one side of the container 103 to produce the cavities within the removal liquid in the interstitial spaces between adjacent surfaces 101-j. Each transducer 121-k provides an acoustic field for one, two or more of the interstitial spaces between two adjacent surfaces 101-j to be cleaned in the container 103. If one or more of the transducers 121-k is not performing properly, the corresponding sonoluminescent response sensed above the diaphragm 109 in the test liquid 111 will not lie in a permitted response range, and the ICCD module 119 will sense this. In this situation, the energy input E(f) and/or the input frequency, $f = f_n$, is adjusted to

bring this portion of the sonoluminescent response into a permitted range, in a manner analogous to the approach discussed in connection with Figures 2 and 3.

The acoustic cavitation field produced in the removal liquid 105 is unlikely to be uniform in the z-coordinate direction, especially if the surfaces 101-j to be cleaned have a relatively large length in the z-direction. Acoustic cavitation is likely to decrease approximately monotonically as z increases, because of the increasing distance from the transducer(s) generating the cavitation.

Uniformity of the acoustic cavitation field in the z-direction can be promoted by varying the chemical composition of the removal liquid 105 within the container 103. Figure 9 schematically illustrates a system 130 to promote uniformity of the acoustic cavitation field, where the surfaces 101-j are now shown in a side view. A sequence of liquid inlets 133-h (h = 1, ... , H; H ≥ 2) and a liquid outlet 135 are provided on opposite sides of the container 103, where the chemical composition received through an inlet 133-h differs from the chemical composition received through at least one of the adjacent inlets, 133-(h-1) and 133-(h+1). This chemical composition is varied to partly or fully compensate for the general decrease in acoustic cavity density with increasing z-coordinate values. The liquid outlet 135 is arranged to encourage flow of the removal liquid 105 substantially in an xy-plane in which this liquid is introduced by a liquid inlet 133-h so that the varying composition introduced at the liquid inlets is approximately maintained as the removal liquid 105 flows (preferably horizontally) toward the liquid outlet 135. The removal liquid 105 may be provided with an additive that provides additional acoustic cavity nucleation sites as the z-coordinate increases. For example, this additive may be carbon particles having diameters of at least 0.5 μm (for easy removal from the surfaces 101-j to be cleaned). In the embodiment shown in Figure 9, the density of nucleation sites or other relevant chemical parameter is varied so that the density of acoustic cavities produced by excitation waves from the transducers 101-j is approximately uniform with variation in the z-coordinate.

Figure 10 schematically illustrates another system 140 for promoting approximate uniformity of acoustic cavity density within the particle removal liquid 105. In Figure 10, a surface 101-j is again viewed on its side, a first set of transducers 141-h1 ($h1 = 1, \ldots, H1$: $H1 \geq 2$) is located at a first end of the surfaces 101-j, and a second set of transducers 142-h2 ($h2 = 1, \ldots, H2$; $H2 \geq 2$) is located at a second, opposed end of the surfaces 101-j. The intensity of the acoustic excitation produced by an individual transducer, 141-h1 or 142-h2, will monotonically decrease as the distance from that transducer increases. As a first approximation, a Beers' law for absorption is adopted, according to which the amplitude $A(y)$ of an acoustic field produced by one of the transducers 141-h1 is approximately $A0\cdot\exp\{-\alpha y\}$, where A0 is an initial amplitude and α (>0) is an amplitude decay parameter that may vary with input frequency f and/or with the chemical and physical nature of the removal liquid. At any location in the removal liquid having a coordinate value y ($0 \leq y \leq L$), the sum of the contributions from the transducers 141-h1 on one side and from the transducers on the other side provides a total amplitude

$$
\begin{aligned}
A(y) &= A0\cdot\exp\{-\alpha y\} + A0\cdot\exp\{-\alpha(L-y)\} \\
&= 2\cdot A0\cdot\exp\{-\alpha L/2)\}\cdot\cosh\{\alpha(y - L/2)\} \\
&\quad 2\cdot A0\cdot\exp\{-\alpha L/2)\}\cdot(1 - (\alpha(y - L/2))^2/2 + O(\,(y - L/2)^4)\} \qquad (4)
\end{aligned}
$$

which has a minimum at $y = L/2$ and increases slowly with increasing coordinate values $|y - L/2|$.. Assuming that a Beers' law absorption is approximately correct here, the maximum fractional difference of the acoustic field amplitude becomes

$$\{A(y=0) - A(y=L/2)\}/A(y=L/2) = \cosh\{\alpha(L/2)\} - 1. \qquad (5)$$

The function $\cosh\{\alpha(L/2)\} - 1$ is monotonically increasing in the variable $\alpha L/2$ and has a value of 0.0984, for example, for $\alpha L/2 = 0.44$; the average acoustic cavitation density is within 10 percent of being uniform for $\alpha L/2$ 0.44.

For a fixed surface length L, this difference can be made smaller by appropriate choice of the removal liquid, where a small value of the decay parameter α is preferred. The embodiment shown in Figures 9 and 10 may be used for cleaning of individual surfaces or for cleaning batches of surfaces. In the

embodiment shown in Figure 10, uniformity of the amplitude of an acoustic field generated by transducers is promoted by a symmetric arrangement of transducers on each of two opposed ends of a surface or an assembly of surfaces.

Another approach to improving the uniformity of average acoustic cavitation density is schematically illustrated in the system 150 in Figure 11. A surface 101-j is again viewed on its side, a first set of transducers 151-h1 ($h1 = 1, \ldots, H1$: $H1 \geq 2$) is located at a first end of the surfaces 101-j, a second set of transducers 152-h2 ($h2 = 1, \ldots, H2$; $H2 \geq 2$) is located at a second, opposed end of the surfaces 101-j, a third set of transducers 153-h3 ($h3 = 1, \ldots, H3$; $H3 \geq 2$), having corresponding transducer lenses 155-h3 and being located at the first end of the surfaces 101-j, and a fourth set of transducers 154-h4 ($h4 = 1, \ldots, H4$; $H4 \geq 2$), having corresponding transducer lenses 156-h3 and being located at the second end of the surfaces 101-j, as shown.

Each transducer lens 155-h3 is "focused" at a positive distance $\Delta y = L/2$ from the first end, and each transducer 156-h4 is "focused" at a positive distance $\Delta y = L/2$ from the second end. The third set and fourth set of focused transducers, 153-h3 and 154-h4, together produce an average acoustic cavitation density that is estimated to be approximately

$$B(y) \quad B0\cdot\exp\{-\beta^2(y - L/2)^2\}, \tag{6}$$

which has a maximum at $y = L/2$ and decreases monotonically as the difference $y = |y - L/2|$ increases. Where only the third and fourth sets of (focused) transducers, 155-h3, 154-h4, 155-h3 and 156-h4, are present, an appropriate measure of uniformity of average acoustic cavitation density is

$$\{B(y{=}L/2) - B(y{=}0)\}/B(y{=}L/2) = 1 - \exp\{-(\beta L/2)^2\}, \tag{7}$$

which can be compared with the measure of uniformity set forth in Eq. (5).

Figure 12 graphically illustrates variation of the density estimates A(y) and B(y) with the location coordinate y. Each of A(y) and B(y) is approximately symmetric about the location value $y = L/2$, with A(y) being monotonically increasing and B(y) being monotonically decreasing with increasing values of $|y - L/2|$.

Where the first and second set of transducers and the third and fourth set of focused transducers are activated simultaneously, the resulting average acoustic cavitation density is approximately the sum

$$\begin{aligned} D(y) &= A(y) + B(y) \\ &= 2\cdot A0\cdot \exp\{-\alpha L/2)\}\cdot \cosh\{\alpha(y - L/2)\} \\ &\quad + B0\cdot \exp\{-\beta^2(y - L/2)^2\}. \end{aligned} \tag{8}$$

Ideally, the parameters A0, B0, α and β are arranged to satisfy

$$0 \lesssim |\, dA/dy + dB/dy \,| < \min\{|\, dA/dy \,|, |\, dB/dy\} \tag{9}$$

so that the average acoustic cavitation density for the combined first, second, third and fourth set of transducers is more uniform, as a function of the variable y, than either the first/second set of transducers or the third/fourth set of transducers. Over a small range of the coordinate difference $\Delta y = |y - L/2|$, including $\Delta y = 0$, the slope magnitude $|dA/dy|$ is at least as large as the slope magnitude $|dB/dy|$. After rearrangement of the terms, over this range (e.g., $|\Delta y| \lesssim \Delta y0$) one requires that

$$\begin{aligned} &(A0/B0)\sinh\{\alpha\, \Delta y\}/\alpha \Delta y \\ &= (A0/B0)\{1 + (\alpha \Delta y)^2/6 + O(\, (\alpha\, \Delta y)^4) \\ &\gtrsim (\beta/\alpha)^2 \exp\{-(\beta/\alpha)^2(\alpha \Delta y)^2\} \\ &= (\beta/\alpha)^2\{1 - (\beta/\alpha)^2(\alpha \Delta y)^2 + O(\, (\beta/\alpha)^4(\alpha \Delta y)^4\}. \end{aligned} \tag{10}$$

The constraint in Eq. (10) is satisfied for a modest range of the variable $\alpha\Delta y$, including $\alpha \Delta y = 0$ in its interior, if the constraint

$$(A0/B0) \gtrsim (\beta/\alpha)^2, \tag{11}$$

is satisfied. More generally, the constraint in Eq. (10) is satisfied for some non-zero range of values of the variable $\alpha \Delta y$. By appropriate choice of the parameters A0, B0, α and β, one can ensure that the difference

$$\begin{aligned} &\{D(y{=}L/2) - D(y{=}0)\}/D(y{=}L/2) \\ &= \{A(y) + B(y) - A(L/2) - B(L/2)\}/\{A(L/2) + B(L/2)\} \quad (0 \lesssim \Delta y \lesssim \Delta y0) \end{aligned} \tag{12}$$

satisfies Eq. (9) so that uniformity of the average acoustical cavitation of the combination is improved vis-a-vis using of the first/second sets of transducers or use of the third/fourth sets of transducers. More generally, one can combine a first

group of transducers with a second group of transducers, having a monotonically increasing cavitation density and a monotonically decreasing cavitation density, respectively, about an interior location (e.g., $y = L/2$, the mid-point) to provide a combined group of transducers having a more uniform cavitation density. Using the transducer systems illustrated in Figures 10 and 11, the average acoustical cavitation density can be made approximately uniform in each of the x-, y- and z-coordinate directions. Transducer systems that produce the cavitation densities A(y) or B(y) or the combination A(y) + B(y) can be used to promote uniformity of average acoustic cavitation densities for the test liquid and/or the particle removal liquid.

Alternatively, one or more of the lensed transducers, 155-h3 and/or 154-h4, can be caused to rotate so that the location of maximum intensity for that transducer within the removal liquid 105 in Figure 11 moves in an approximately circular sector pattern in the yz-plane. This will cause the location $(x,y,z)_{max}$ of maximum intensity corresponding to the rotating transducer to vary along that circular sector (dotted line in Figure 11). Where a plurality of the lensed transducers are caused to rotate in this manner,

Each of the lensed transducers, 155-h3 and 156-h4, in Figure 11 can be replaced or supplemented with one or more non-planar shaped transducers 157-h5, as illustrated in Figure 13, preferably with a concave or undulating shape factor $h = h(z)$ that causes the transducer energy received at any location (x,y,z) in the particle removal liquid 105 to achieve a maximum value, not close to the side wall (x · 0), but at a selected positive distance $x = d_{max}(z)$, which may vary with the distance z along the side wall. For example, if the shape factor is approximately sinusoidal (e.g., $h(z) \approx h_0 - h_1 \sin\kappa z$), the distance $d_{max}(z)$ will also vary approximately periodically with period $2\pi/\kappa$, as suggested in Figure 13.

In Figure 14, a sensor plate 170 containing an array of acoustic cavity sensors 171-j ($j = 1, \ldots, J$; $J \geq 2$) is positioned in a container 172 containing particle removal liquid 173. An array of acoustic cavity transducers 174-k ($k = 1, \ldots, K$; $K \geq 2$) is positioned on a wall 175 of the container 172, and a plane of the

sensor plate 170 is substantially parallel to a plane of the transducer wall 175, with a selected separation distance d ($\approx$ 0.5 - 5 cm). The array of transducers 174-k is activated and produces a two-dimensional spatial distribution D(x,y;t) of acoustic cavities 176 within the particle removal liquid 173 that are sensed and a time average D(x,y;avg) is formed over a time interval of selected temporal length t(avg), such as 0.5 - 15 sec. A reference or ideal distribution of cavities for an ideal distribution of cavities D(x,y;ref) is provided, and a selected non-negative combination C{D(x,y;avg),D(x,y;ref)} is formed and compared with a threshold value C_{thr} for a selected sequence $\{(x_i,y_i)\}_i$ of I locations (I $\gtrsim$ 2) on or adjacent to the array of transducers 174-k. The combination C is preferably homogeneous of degree β in the sense that

$$C\{\alpha D(x,y;avg),\alpha D(x,y;ref)\} = |\alpha|^{\beta}\, C\{D(x,y;avg),D(x,y;avg;ideal)\}, \qquad (13)$$

where α is an arbitrary real number and β is a fixed real number (including 0) that is characteristic of the combination C. Ideally, the combination C is 0 when the measured distribution is the same as the reference distribution, and, optionally,

$$C\{D(x,y;test),D(x,y,test)\} = 0 \qquad (14)$$

for any (arbitrary) test distribution of cavities D(x,y;test).

If, for example, the combination C is a difference, the threshold requirement is stated as

$$C\{D(x,y;avg),D(x,y;ref)\} = \{\sum_{i=1}^{I} w_i\, |D(x_i,y_i;avg) - D(x_i,y_i;ref)|^{\mu}\}^{1/\mu} \lesssim C_{thr}, \qquad (15)$$

where $\{w_i\}_i$ is a selected set of non-negative weighting coefficients (with sum = 1), μ is a selected non-zero constant (positive or negative) and C_{thr} is a suitable small fraction of a spatial average <D(x,y;avg.ref)> over all pairs (x,y). By choosing $w_i = 1/I$ for all i and $\mu = 1$, one requires that the sum of the differences be no greater than C_{thr}. If the combination C is a ratio, a threshold requirement is

C{D(x,y;avg),D(x,y;ref)}.

$$= \{\sum_{i=1}^{I} w_i \, |D(x_i,y_i;avg)/D(x_i,y_i;ref) - 1|^{\mu}\}^{1/\mu} \lesssim C'_{thr}, \tag{16}$$

where C'_{thr} is a suitable small fraction, such as 0.1. Another suitable combination C and associated threshold requirement is

$$C\{D(x,y;avg),D(x,y;ref)\}$$
$$= \{\sum_{i=1}^{I} w_i \, |D(x_i,y_i;avg)/D(x_i,y_i;ref)|^{\mu}\}^{1/\mu} \gtrsim C''_{thr}, \tag{17}$$

where C''_{thr} is a suitable fraction, such as 0.9. More generally, the combination C can be defined as

$$C\{D(x,y;avg),D(x,y;ref)\}$$
$$= \sum_{i=1}^{I} w_i \, F\{D(x_i,y_i;avg)/D(x_i,y_i;ref)\}, \tag{18}$$

where F(r) is a monotonically increasing function, or a monotonically decreasing function, of the variable r, with a corresponding threshold condition ($C \lesssim C_{thr}$ or $C \gtrsim C_{thr}$).

If the value of the combination C satisfies the associated threshold test, the transducer array is accepted; otherwise, the performance of the transducer array is determined to be non-acceptable. This approach provides a virtual wafer, the plate 170, for monitoring the acoustic cavity distribution produced by a transducer array.

Figure 15 schematically illustrates another system 181 for batch cleaning of wafers Wk ($k = 1, \ldots, K$; $K \gtrsim 2$). In Figure 15, K = 8. The wafer Wk is received and held on a wafer receiving surface WRSk, which is spun about a wafer axis (not explicitly shown in Figure 15) that is oriented perpendicular to the plane of the paper. A cleaning liquid delivery propeller system 183 is positioned above, and delivers a selected cleaning liquid to, a wafer Wk. Two or more cleaning liquids (the same or different liquids) can be delivered sequentially to a wafer Wk,

and the wafer is spun about its wafer axis. The liquid spears over the a rotating exposed surface of the wafer Wk through centrifugal force, and the excess liquid is spun off the wafer surface for recapture or disposal.

Figure 16 schematically illustrates an embodiment 201 for delivery and recapture of one or several cleaning liquids according to the invention. A wafer-receiving rotating plate 203 receives and holds a wafer W. The plate 203 and wafer W are caused to rotate by an attached spindle 205 having a spin axis AA and being driven by a motor 206. Two or more cleaning liquids are delivered sequentially through a cleaning liquid delivery tube 207, where the cleaning liquid is directed at one or more exposed surfaces WES of the wafer W. The liquid delivery tube 207 may be a sequence of adjacent tubes for improved coverage of the wafer exposed surface WES. The wafer plate 203, wafer W, spindle 205 and cleaning liquid delivery tube 207 are positioned within a system container 209 as shown. Cleaning liquid no. q ($q = 1, 2, \ldots, Q$; $Q \geq 2$; $Q=3$ in Figure 16) is delivered by the delivery tube 207 when a plane of the wafer exposed surface WES is located at a vertical level Lq. The cleaning liquids may be the same or different. For example, three different liquids can be applied sequentially, in spaced apart time intervals, to perform corresponding steps in an overall cleaning process.

Where, for example, three (optionally different) cleaning liquids are delivered sequentially to the wafer W, a first liquid recapture or withdrawal mechanism 211, a second liquid recapture mechanism 213 and a third liquid recapture mechanism 215 are spaced apart from each other, parallel to but spaced apart from the axis AA.. In a corresponding cleaning sequence, a first cleaning liquid is delivered to an exposed surface of the wafer W by the liquid delivery tube 207 when the wafer exposed surface WES is approximately aligned with the first liquid recapture mechanism 211 so that the first cleaning liquid that is spun off the wafer surface WES is received or recaptured by recapture mechanism 211 and temporarily held in a first liquid recapture receptacle 221, for subsequent liquid draw-off through a first draw-off tube 231, for disposal or reprocessing.

[redacted]

In a similar manner, a second cleaning liquid is delivered to the wafer exposed surface WES by the liquid delivery tube 207 when the wafer exposed surface is approximately aligned with the second liquid recapture mechanism 213 so that the second cleaning liquid that is spun off the wafer surface WES is received or recaptured by recapture mechanism 213 and temporarily held in a second liquid recapture receptacle 223, for subsequent liquid draw-off through a second draw-off tube 233. Delivery and recapture of a third cleaning liquid at a third recapture mechanism 225 is similar.

Optionally, each of the liquid recapture mechanisms, 211, 213 and 215, has a corresponding liquid entry valve, 212, 214 and 216, that is opened when the wafer exposed surface WES is aligned with the corresponding liquid recapture mechanism, and the valve is closed at all other times. The first, second and third cleaning liquids are delivered during first, second and third time intervals that are spaced apart from each other so that a given cleaning liquid can only enter the liquid recapture mechanism that corresponds to the correct cleaning liquid. As a given cleaning liquid is delivered by the delivery tube 207 onto the wafer exposed surface WES, the liquid spreads over the rotating surface WES through centrifugal force, and the excess liquid is received by the corresponding recapture mechanism, whose valve is open to receive the given liquid.

Transducer action that is initially required to establish an acoustic cavitation field may differ from transducer action required (or sufficient) to maintain the field. Where the initial and maintenance transducer action are different, one or more transducer parameters (e.g., activation energy and/or transducer frequency) is changed after the field is initially established. For example, the transducer activation energy may need to be reduced after the field is established, as suggested by some experimental results reported by G. Ferrell et al in "A novel cavitation probe design and some preliminary measurements of its application to megasonic cleaning," Jour. Acoust. Soc. Amer., vol. 112 (2002) pp. 1196-1202. As illustrated graphically in Figure 17, (cavitation brightness versus time for transducer power levels of 50, 100, 200, 300, 400 and 500 Watts), imposition of

too much cavitation may interfere with propagation of the acoustic field. This interference may increase non-uniformity of the cavitation density, an undesirable effect, or cause damage of the object surface, as illustrated in Figure 18 by distortion of initially parallel lines in an object surface.

A first alternative approach involves initial addition of an inert fluid, such as Ne or Ar, to the initial test fluid or particle removal fluid, to encourage initial formation of acoustical cavities; after which the inert fluid is withdrawn or the inert fluid concentration is changed in a timed manner, for example, by bleeding off liquid that contains the inert fluid. Timed variation of one or more transducer parameters, as the acoustical cavitation field is initially established and subsequently maintained, promotes approximately uniform cavitation density in a fourth dimension, time.

In a second alternative approach, application of the cavitation energy may be given a "soft start," in which the transducer power is ramped up slowly rather than substantially instantaneously, in order to suppress appearance of a sharp maximum in photons observed (as in Figure 17) and to suppress this interference.

In a third alternative approach, the transducer power is ramped up slowly and, after cavitation energy is approaching an asymptote, the inert fluid from the first approach is introduced into the test fluid or particle removal fluid.

In a fourth alternative approach, intended to avoid damage to the object surface, transducer power is ramped up to a desired final value, without presence of the object to be cleaned; the object(s) is then immersed in the test liquid or particle removal liquid; and the process continues as discussed in the preceding.

Each of an array of three or more transducers may be independently driven at a timed sequence of differing frequencies, in order to provide a pseudo-chaotic cavitation field that changes as the frequencies change from moment to moment. That is, each transducer is driven by a frequency hopping sequence that is similar to a sequence used in spread spectrum communications. For example, if five frequencies, f_k ($k = 1, \dots, 5$) are available for each transducer, three transducers may be driven with the following frequency sequences:

Trans. 1	f_1	f_3	f_5	f_2	f_4	f_1	f_4	f_2	f_5	f_3	f_1	f_5
Trans. 2	f_2	f_5	f_4	f_1	f_3	f_5	f_3	f_4	f_1	f_2	f_3	f_4
Trans. 3	f_5	f_1	f_2	f_4	f_1	f_3	f_2	f_3	f_4	f_5	f_1	f_2.

Preferably, the frequencies are non-commensurate with each other so that a relationship $m \cdot f_{k1} \approx n \cdot f_{k2}$ cannot be found for small positive integers m and n. Preferably, for a given transducer, the frequency hops from one value to a succeeding value in a time interval of 10^{-6} - 10^{-2} sec, and the frequency transition times differ for each of the transducers. This approach will produce a chaotic acoustic excitation field in which the cavitation density, averaged over a short time interval with a length of the order of 0.1 sec or less, will be approximately uniform from one location to another within the liquid.

Preferably, each transducer has a permitted, approximately continuous range of frequencies, $f_{min} \lesssim f \lesssim f_{max}$, over which the transducer can be operated, where the quantity $r_f - (f_{max} - f_{min})/(f_{max} + f_{min})$ is as large as a few percent. As an alternative to discrete frequency hopping, the operating frequency of each of the transducers can be swept across a selected range according to

$$f(oper) = r_f(t) \cdot f_{min} + (1 - r_f(t)) \cdot f_{max}, \qquad (19)$$

where the sweep rate (proportional to dr_f/dt) for each transducer is non-commensurate with the sweep rate for all other transducers and the minimum and maximum frequency values for each transducer are different.

When a wafer is subjected to liquid cavitation from acoustic waves, the wafer should not be tightly attached to the wafer holder. Tight attachement of the wafer to the wafer holder allows or encourages development of an equivalent of Newton's rings, with permanent locations of peaks and valleys, on a wafer surface, arising in part from "illumination" of the partly constrained wafer surface by acoustic waves, analogous to mechanical excitation of a partly constrained membrane. Where a wafer is very loosely held in a wafer holder so that no point on the wafer surface is a permanent node that is fixed in location, the acoustic waves will provide random patterns that vary from one time to another so that, on

average, no region of the wafer surface is subjected to substantially more, or substantially less, acoustic cavitation effects than is any other region on the wafer surface. Development of the equivalent Newton's rings with more or less fixed locations on a wafer surface will produce undesirable and substantial differences in time-averaged cavitation density effects on different regions of the wafer surface.

In a first approach to remove or suppress the effects of presence of equivalent Newtons rings with fixed locations, a wafer held in a wafer holder may be allowed to move laterally in a range of 0.1 – 5 times the wafer thickness (or greater) in order to approximate a completely free wafer and to avoid appearance of equivalent Newtons rings with fixed locations.

In a second approach to remove or suppress the effects of presence of equivalent Newtons rings with fixed locations, illustrated in Figure 19, a vector normal to a plane Π defining the wafer surface is dithered in time by an angle $\Delta\Phi$ in a range $0.2^\circ - 10^\circ$ (preferably no more than about 2°) to approximate a completely free wafer. In Figure 19, a wafer 222 is attached to a wafer chuck 223 and/or to a shaft 224, and the shaft angle $\Delta\Phi$ is dithered, using a random or pseudo-random angle orientation pattern for the shaft.

As the number of activated acoustic cavitation transducers increases, the cleaning liquid in which the transducers are located becomes "brighter" in the sense that an average color value associated with the acoustic wave field increases monotonically from a "dark" color value (with no transducer activated) toward higher color values that correspond to progressively brighter acoustic cavitation wave fields. This increase in color value is nearly, but not strictly, linear, as illustrated graphically in Figure 20, which indicates variation in color value with an increase in number of adjacent activated transducers within a test liquid or cleaning liquid at an output frequency of 1 MHz and input power to each transducer corresponding to about 4 Volts.

Figures 21A, 21B, 21C and 21D are photographs of light (photon counts) produced by an acoustic cavitation wave field where u = 3, 5, 7 and 9 adjacent

[redacted]

transducers are activated in a cleaning liquid (here, DI water). Each of these photographs has a first region, adjacent to location of the activated transducers, that is relatively brighter than a second, relatively dark region. The numerical area of the first region and its associated brightness increase faster than linearly with the number u of activated transducers (roughly as the square of the number u). This is surprising and indicates presence of one or more synergistic effects associated with the number u of adjacent activated transducers. If each of the activated transducers was substantially isolated from each of the other activated transducers, the numerical area of the first region would likely increase linearly with u, and the associated brightness would likely be approximately constant with increasing u.

This monotonic increase in brightness, with increase in number u of adjacent activated transducers, expressed as

$$\phi = f(u), \tag{20}$$

can be combined with an estimate,

$$\chi = g(\beta), \tag{21}$$

of the cleaning capability of the acoustic cavitation field corresponding to the brightness ϕ. This combination will provide an estimate of the number u of adjacent activated transducers needed to provide a given cleaning power χ (e.g., average number of particles removed from a surface per unit surface area and per unit time), by inverting the expression

$$\chi = g\{f(u)\} \tag{22}$$

To obtain u as a function of χ. The ϕ versus u relationship in Eq. (20) can be obtained by observation. The χ versus ϕ relationship in Eq. (21) will need to be experimentally determined for each particle removal liquid, each transducer power level, each type of particle to be removed, and each object surface (e.g., a wafer surface) of interest. Where only a short time interval (e.g., 15 sec) can be devoted to particle removal on a given surface, the number u of adjacent activated transducers will need to be increased relative to the number used for a longer exposure time (e.g., 60 sec).

Figures 22A and 22B are images representing cavitation density for a nin-transducer array, where the applied voltage is uniformly 5 Volts (Figure 22A), and where the applied voltage is varied from 3.4 to 4.7 Volts for each transducer in order to provide a more uniform density. Each image was formed using an exposure of about 2.5 sec. Figure 22A indicates presence of several "hot spots" and "cold spots" where the cavitation density may produce (i) damage to the object surface and/or (ii) unacceptable variations in the particles remaining on the object surface.

Appearance of observable acoustic cavitation is a threshold event, depending upon the presence of several variables, not all of which have yet been identified. Variables that are known to affect the presence or absence of observable acoustic cavitation include: number of active and adjacent transducers; electrical power applied to each active transducer; transducer frequency(ies) applied; presence (or absence) and concentration of a fluid that helps promote cavitation; surface tension of the particle removal or test liquid; and temperature of the particle removal or test liquid. Use of a non-optimum value for one of these variables can be compensated for by use of a more optimum value of one or more of the other variables.

The embodiments illustrated herein are suitable for single wafer processing or batch processing of wafers (especially those illustrated in Figures 8-11 and 13-16). By smoothly varying the acoustic cavitation density with location on a wafer surface, this density can be adjusted to compensate for the effects of linear velocity V of different small regions of the wafer surface, where V varies (approximately linearly) with radial distance r from the axis of wafer rotation.

What is claimed is:

1. A method for removal of one or more particles attached to a solid surface, the method comprising:

providing an assembly of two or more activatable transducers, with each transducer being capable of generating at least one cavity in a selected particle removal liquid, where the generated cavity subsequently collapses and provides a mechanism for removal of at least one particle attached to a solid surface suspended in the particle removal liquid;

immersing the transducer assembly in a selected test liquid;

activating a first transducer in the assembly to produce at least one cavity in the test liquid, estimating a first representative cavitation density $\rho_{cav}(1)$ produced by the first transducer and computing a first difference, $|\rho_{cav}(1) - \rho_{cav}(ref)|$, where $\rho_{cav}(ref)$ is a selected reference cavitation density,

when the magnitude of the first difference is greater than a selected difference threshold $\Delta\rho_{thr}$, adjusting at least one parameter on the first transducer so that at least one of the following conditions is satisfied: (i) the magnitude of the first difference is reduced to no greater than the difference threshold and (ii) the magnitude of the first difference is minimized;

activating a second transducer in the assembly to produce at least one cavity in the test liquid, estimating a second representative cavitation density $\rho_{cav}(2)$ produced by the second transducer, and computing a second difference, $|\rho_{cav}(2) - \rho_{cav}(ref)|$;

when the magnitude of the second difference is greater than $\Delta\rho_{thr}$, adjusting at least one parameter on the second transducer so that at least one of the following conditions is satisfied: (i) the magnitude of the second difference is reduced to no greater than the difference threshold and (ii) the magnitude of the second difference is minimized;

removing the transducer assembly from the test liquid and immersing the transducer assembly in the particle removal liquid; and

activating at least the first and second transducers in the particle removal liquid, and allowing at least one cavity produced by at least one of the first and second transducers to collapse and to thereby remove at least one particle attached to the solid surface immersed in the particle removal liquid.

2. The method of claim 1, further comprising selecting said particle removal liquid and said test liquid to be substantially the same liquid.

3. The method of claim 1, further comprising selecting said particle removal liquid from the group of liquids consisting of H_2O, NH_3, H_2O_2, H_2SO_4 and O_3 dissolved in DI water.

4. The method of claim 1, further comprising selecting said test liquid from the group of liquids consisting of DI water and DI water plus an inert fluid drawn from Ne, Ar, Kr and Xe.

5. The method of claim 1, further comprising causing each of said first transducer and said second transducer to emit a first signal having a first selected output frequency and a second signal having a second selected output frequency, respectively, in said particle removal liquid, where each of the first and second output frequencies is in a range 100-3000 KHz..

5A. The method of claim 1, further comprising:

suspending at least a second solid surface in said particle removal liquid, when said first and second transducers are activated; and

allowing at least one additional cavity produced by at least one of said first transducer and said second transducer to collapse and to thereby remove at least one particle attached to the second solid surface immersed in said particle removal liquid.

[redacted]

6. A system for removal of one or more particles attached to a solid surface, the system comprising:

a container of a selected test liquid that receives an assembly of two or more activatable transducers, with each transducer being capable of generating at least one cavity in a selected particle removal liquid, where the generated cavity subsequently collapses and provides a mechanism for removal of at least one particle attached to a solid surface suspended in the particle removal liquid;

a first transducer activation and measurement mechanism to activate a first transducer in the assembly to produce at least one cavity in the test liquid, to estimate a first representative acoustic cavitation density $\rho_{cav}(1)$ produced by the first transducer, and to compute a first difference, $|\rho_{cav}(1) - \rho_{cav}(ref)|$, where $\rho_{cav}(ref)$ is a selected reference cavity diameter,

a first transducer adjustment mechanism configured so that, when the magnitude of the first difference is greater than a selected difference threshold $\Delta\rho_{thr}$, at least one parameter on the first transducer is adjusted so that at least one of the following conditions is satisfied: (i) the magnitude of the first difference is reduced to no greater than the difference threshold and (ii) the magnitude of the first difference is minimized;

a second transducer activation and measurement mechanism to activate a second transducer in the assembly to produce at least one cavity in the test liquid, to estimate a representative pre-implosion cavity diameter $\rho_{cav}(2)$, and to compute a second difference, $|\rho_{cav}(2) - \rho_{cav}(ref)|$;

a second transducer adjustment mechanism configured so that, when the magnitude of the second difference is greater than $\Delta\rho_{thr}$, at least one parameter on the second transducer is adjusted so that at least one of the following conditions is satisfied: (i) the magnitude of the second difference is reduced to no greater than the difference threshold and (ii) the magnitude of the second difference is minimized;.

[redacted]

an assembly repositioning mechanism to remove the transducer assembly from the test liquid and to immerse the transducer assembly in the particle removal liquid; and

a transducer assembly activation mechanism to activate at least the first and second transducers in the particle removal liquid, and to allow at least one cavity produced by at least one of the first and second transducers to collapse and to thereby remove at least one particle attached to the solid surface immersed in the particle removal liquid.

7. The system of claim 6, wherein said particle removal liquid and said test liquid are substantially the same liquid.

8. The system of claim 6, wherein said particle removal liquid is drawn from the group of liquids consisting of H_2O, NH_2, H_2O_2, H_2SO_4 and O_3 dissolved in DI water.

9. The system of claim 6, wherein said test liquid is drawn from the group of liquids consisting of DI water and DI water plus an inert fluid drawn from Ne, Ar, Kr and Xe.

10. The system of claim 6, wherein each of said first transducer and said second transducer is caused to emit a first signal having a first selected output frequency and a second signal having a second selected output frequency, respectively, in said particle removal liquid, where each of the first and second output frequencies lies in a range 100-3000 KHz.

10A. The system of claim 6, wherein:

a second solid surface is suspended in said particle removal liquid, when said first and second transducers are activated; and

[redacted]

at least one of said first and second transducers, when activated, produces at least a second cavity that collapses and thereby removes at least one particle attached to the second solid surface immersed in said particle removal liquid.

11. A method for removal of one or more particles attached to a solid surface, the method comprising:

providing an assembly of I activatable transducers, with $I \geq 2$, with each transducer being capable of generating at least one cavity in a selected particle removal liquid, where the generated cavity subsequently collapses and provides a mechanism for removal of at least one particle attached to a solid surface suspended in the particle removal liquid;

immersing the transducer assembly in a selected test liquid;

activating each of a subset of I' transducers in the assembly, numbered $i' = 1, \ldots, I'$, with $1 < I' \leq I$. to produce at least one cavity in the test liquid for each activated transducer in the subset, estimating a representative cavitation density $\rho_{cav}(i')$ produced by transducer number i', and computing a density difference, $\Delta\rho(i') = |\rho_{cav}(i') - \rho_{cav}(ref)|$, for each of $i' = 1, \ldots, I'$, where $\rho_{cav}(ref)$ is a selected reference cavitation density,

forming a statistical average $D\{\Delta\rho(i1), \ldots, \Delta\rho(I')\}$ of the I' density differences;

when the statistical average $D\{\Delta\rho(i1), \ldots, \Delta\rho(I')\}$ is greater than a selected difference threshold $\Delta\rho_{thr}$, adjusting at least one parameter for at least one of the I' transducers so that at least one of the following conditions is satisfied: (i) the statistical average $D\{\Delta\rho(i1), \ldots, \Delta\rho(I')\}$ after the adjustment is reduced to a value no greater than the difference threshold and (ii) the magnitude of the statistical average $D\{\Delta\rho(i1), \ldots, \Delta\rho(I')\}$ is minimized;

removing the transducer assembly from the test liquid and immersing the transducer assembly in the particle removal liquid; and

activating at least the I' transducers in the particle removal liquid, and allowing at least one cavity produced by at least one of the I' transducers to

collapse and to thereby remove at least one particle attached to the solid surface immersed in the particle removal liquid.

12. The method of claim 11, further comprising choosing said statistical average to be given approximately by

$$D(\Delta\rho(1'), \ldots, \Delta\rho(I')) = \{\sum_{i'=1}^{I'} w(i')\cdot\{\Delta\rho(i')\}^{p}\}^{1/p},$$

where p is a selected positive number and w(i') is a non-negative weight coefficient satisfying a constraint

$$\sum_{i'=1}^{I'} w(i') = 1.$$

13. The method of claim 11, further comprising selecting said particle removal liquid and said test liquid to be substantially the same liquid.

14. The method of claim 11, further comprising selecting said particle removal liquid from the group of liquids consisting of H_2O, NH_2, H_2O_2, H_2SO_4 and O_3 dissolved in DI water.

15. The method of claim 11, further comprising selecting said test liquid from the group of liquids consisting of DI water and DI water plus an inert fluid drawn from Ne, Ar, Kr and Xe.

15A. The method of claim 11, further comprising:

suspending at least a second solid surface in said particle removal liquid, when said first and second transducers are activated; and

allowing at least one additional cavity produced by at least one of said first transducer and said second transducer to collapse and to thereby remove at least

[redacted]

one particle attached to the second solid surface immersed in said particle removal liquid.

16. A system for removal of one or more particles attached to a solid surface, the system comprising:

an assembly of I activatable transducers, with $I \geqslant 2$, with each transducer being capable of generating at least one cavity in a selected particle removal liquid, where the generated cavity subsequently collapses and provides a mechanism for removal of at least one particle attached to a solid surface suspended in the particle removal liquid;

a first container of a selected test liquid in which the transducer assembly can be immersed;

a transducer activation mechanism for activating each of a subset of I' transducers in the assembly, numbered $i' = 1, \ldots, I'$, with $1 < I' \lesssim I$. to produce at least one cavity in the test liquid for each activated transducer in the subset, where the activation mechanism estimates a representative cavitation density $\rho_{cav}(i')$ produced by transducer number i' and computes a density difference, $\Delta\rho(i') = |\rho_{cav}(i') - \rho_{cav}(ref)|$, for each of $i' = 1, \ldots, I'$, where $\rho_{cav}(ref)$ is a selected reference cavitation density,

a computing device that is programmed to:

receive the estimated representative cavitation densities $\rho_{cav}(i')$ and forms a statistical average $D\{\Delta\rho(i1), \ldots, \Delta\rho(I')\}$ of the I' density differences; and

when the statistical average $D\{\Delta\rho(i1), \ldots, \Delta\rho(I')\}$ is greater than a selected difference threshold $\Delta\rho_{thr}$, to adjust at least one parameter for at least one of the I' transducers so that at least one of the following conditions is satisfied: (i) the statistical average $D\{\Delta\rho(i1), \ldots, \Delta\rho(I')\}$ after the adjustment is reduced to a value no greater than the difference threshold and (ii) the magnitude of the statistical average $D\{\Delta\rho(i1), \ldots, \Delta\rho(I')\}$ is minimized;

an assembly removal mechanism for removing the transducer assembly from the test liquid and immersing the transducer assembly in a second container containing the particle removal liquid; and

where the transducer activation mechanism activates at least the I' transducers in the particle removal liquid, and allows at least one cavity produced by at least one of the I' transducers to collapse and to thereby remove at least one particle attached to the solid surface immersed in the particle removal liquid.

17. The system of claim 16, wherein said computing device is further programmed to choose said statistical average to be given approximately by

$$D(\Delta\rho(1'), \ldots, \Delta\rho(I')) = \{\sum_{i'=1}^{I'} w(i')\cdot\{\Delta\rho(i')\}^{p}\}^{1/p},$$

where p is a selected positive number and w(i') is a non-negative weight coefficient satisfying a constraint

$$\sum_{i'=1}^{I'} w(i') = 1.$$

18. The system of claim 16, wherein said particle removal liquid and said test liquid are substantially the same liquid.

19. The system of claim 16, wherein said particle removal liquid is drawn from the group of liquids consisting of H_2O, NH_3, H_2O_2, H_2SO_4 and O_3 dissolved in DI water.

20. The system of claim 16, wherein said test liquid is drawn from the group of liquids consisting of DI water and DI water plus an inert fluid drawn from Ne, Ar, Kr and Xe.

20A. The system of claim 16, wherein:

a second solid surface is suspended in said particle removal liquid, when said first and second transducers are activated; and

at least one of said first and second transducers, when activated, produces at least a second cavity that collapses and thereby removes at least one particle attached to the second solid surface immersed in said particle removal liquid.

21. A method for removal of one or more particles attached to a solid surface, the method comprising:

providing a first liquid container containing a selected particle removal liquid;

providing a thin sheet of a selected solid material at an exposed surface of the removal liquid so that a first surface of the thin sheet is contacted by the removal liquid;

providing at least one transducer adjacent to a selected first wall of the container;

positioning a first surface of a first object and a first surface of a second object spaced apart from and substantially parallel to each other in the first container, where each of the first surfaces has a first end and has a second end, the first end of each of the first surfaces is adjacent to the at least one transducer, the second end of each of the first surfaces is adjacent to the thin sheet, and each of the first surfaces has at least one particle to be removed therefrom;

providing a test liquid in contact with a second surface of, and on an opposite side of, the thin sheet from the thin sheet first surface;

positioning a light sensor adjacent to an exposed surface of the test liquid to receive and sense light produced in the test liquid; and

activating the at least one transducer to thereby generate and allow collapse of at least one acoustic cavity within the removal liquid, to thereby receive at the thin sheet first surface a first energy pulse arising from the collapse of the at least

[redacted]

one cavity, and to generate in the test liquid a second energy pulse in response to receipt of the first energy pulse at the thin sheet first surface.

22. The method of claim 21, further comprising choosing, as said first container wall, a wall that faces said thin sheet.

23. The method of claim 22, further comprising providing at least first and second sources of first and second selected liquid chemicals, respectively, on a second wall of said container that extends from said first container wall toward said removal liquid exposed surface, where the first source is positioned between said first container wall and the second source and where said first energy pulse is more readily generated in a mixture of said removal liquid and the second liquid chemical than in a mixture of said removal liquid and the first liquid chemical.

24. The method of claim 23, further comprising selecting at least one of said first chemical and said second chemical to include at least one of Ne, Ar, Kr and Xe.

25. The method of claim 21, further comprising:

providing, as said at least one transducer, (i) a first transducer on said first container wall that is adjacent to and extends toward said thin sheet and (ii) a second transducer on a second container wall that is spaced apart from and faces said first container wall; and

activating the first and second transducers at respective first and second activation levels so that a concentration of said acoustic cavities generated in said removal liquid is approximately uniform along a line segment extending between said first container wall and the second container wall.

26. The method of claim 25, further comprising configuring said first transducer and said second transducer so that (1) said concentration of said

acoustic cavities generated by said first transducer decreases approximately monotonically as a location on said line segment moves from said first container wall toward a center of said line segment and (2) said concentration of said acoustic cavities generated by said second transducer decreases approximately monotonically as a location on said line segment moves from said second container wall toward the center of said line segment.

27. The method of claim 26, further comprising:

providing (iii) a third transducer on said first container wall, adjacent to said first transducer and extending toward said thin sheet and (iv) a fourth transducer on said second container wall, adjacent to said second transducer and extending toward said thin sheet, where the third and fourth transducers are configured so that (3) concentration of said acoustic cavities generated by said third transducer increases approximately monotonically as a location on said line segment moves from said first container wall toward said center of said line segment and (4) concentration of said acoustic cavities generated by said fourth transducer increases approximately monotonically as a location on said line segment moves from said second container wall toward said center of said line segment.

27A. The method of claim 26, further comprising causing an acoustic field generated by at least one of said first transducer and said second transducer to rotate with passage of time in a plane containing said line segment that extends between said first container wall and the second container wall so that said concentration of said acoustic cavities generated in said particle removal liquid varies with the passage of time.

27B. The method of claim 26, further comprising generating said acoustic cavities generated by at least one of said first transducer and said second transducer so that said concentration of said cavities is non-uniform along at least one second line segment within said particle removal liquid that extends

substantially parallel to at least one of said first container wall and said second container wall.

28. The method of claim 25, further comprising configuring said first transducer and said second transducer so that (1) said concentration of said acoustic cavities generated by said first transducer increases approximately monotonically as a location on said line segment moves from said first container wall toward a center of said line segment and (2) said concentration of said acoustic cavities generated by said second transducer increases approximately monotonically as a location on said line segment moves from said second container wall toward the center of said line segment.

29. The method of claim 25, further comprising configuring said first transducer and said second transducer so that said concentration of said acoustic cavities generated in said particle removal liquid is approximately equal to $a + b \cdot \cosh\{\alpha(x-L/2)\}$, where a, b and α are selected constants with b and α positive, x is a location coordinate measured in a direction extending between said first and second container walls, and L is a distance of separation between said first and second container walls.

30. The method of claim 25, further comprising configuring said first transducer and said second transducer so that said concentration of said acoustic cavities generated in said particle removal liquid is approximately proportional to $a + c \cdot \exp\{-\beta^2(x-L/2)^2\}$, where a, c and β are constants, with c and β positive, x is a location coordinate measured in a direction extending between said first and second container walls, and L is a distance of separation between said first and second container walls.

31. The method of claim 25, further comprising configuring said first transducer and said second transducer so that said concentration of said acoustic cavities generated in said particle removal liquid is approximately proportional to $a + b \cdot \cosh\{\alpha(x-L/2)\} + c \cdot \exp\{-\beta^2(x-L/2)^2\}$, where a, b, c, α and β are constants, with b, c, α and β positive, x is a location coordinate measured in a direction extending between said first and second container walls, and L is a distance of separation between said first and second container walls.

31A. The method of claim 28, further comprising causing an acoustic field generated by at least one of said first transducer and said second transducer to rotate with passage of time in a plane containing said line segment that extends between said first container wall and the second container wall so that said concentration of said acoustic cavities generated in said particle removal liquid varies with the passage of time.

31B. The method of claim 28, wherein said concentration of said acoustic cavities generated by at least one of said first transducer and said second transducer is non-uniform along at least one second line segment within said particle removal liquid that extends substantially parallel to at least one of said first container wall and said second container wall.

32. The method of claim 21, further comprising selecting said particle removal liquid and said test liquid to be substantially the same liquid.

33. The method of claim 21, further comprising selecting said particle removal liquid from the group of liquids consisting of H_2O, NH_3, H_2O_2, H_2SO_4 and O_3 dissolved in water.

34. The method of claim 21, further comprising selecting said test liquid from the group of liquids consisting of DI water and DI water plus an inert fluid drawn from Ne and Ar.

35. The method of claim 21, further comprising causing said at least one transducer to emit a first signal having a first selected output frequency or, alternatively, to emit a second signal having a second selected output frequency, respectively, in said particle removal liquid, where each of the first and second output frequencies is in a range 100-3000 KHz.

36. A system for removal of one or more particles attached to a solid surface, the system comprising:

a first liquid container containing a selected particle removal liquid;

a thin sheet of a selected solid material, positioned at an exposed surface of the removal liquid so that a first surface of the thin sheet is contacted by the removal liquid;

at least one transducer positioned adjacent to a selected first wall of the container;

where the first container receives a first surface of a first object and a first surface of a second object spaced apart from and substantially parallel to each other in the first container, each of the first surfaces has a first end and has a second end, the first end of each of the first surfaces is adjacent to the at least one transducer, the second end of each of the first surfaces is adjacent to the thin sheet, and each of the first surfaces has at least one particle to be removed therefrom;

a second liquid container containing a test liquid in contact with a second surface of, and on an opposite side of, the thin sheet from the thin sheet first surface;

a light sensor positioned adjacent to an exposed surface of the test liquid to receive and sense light produced in the test liquid; and

transducer activation means to activate the at least one transducer to thereby generate and allow collapse of at least one acoustic cavity within the removal liquid, to thereby receive at the thin sheet first surface a first energy pulse arising from the collapse of the at least one cavity, and to generate in the test liquid a second energy pulse in response to receipt of the first energy pulse at the thin sheet first surface.

37. The system of claim 36, wherein said first container wall is a wall that faces said thin sheet.

38. The system of claim 37, further comprising at least first and second sources of first and second selected liquid chemicals, respectively, positioned on a second wall of said container that extends from said first container wall toward said removal liquid exposed surface, where the first source is positioned between said first container wall and the second source and where said first energy pulse is more readily generated in a mixture of said removal liquid and the second liquid chemical than in a mixture of said removal liquid and the first liquid chemical.

39. The system of claim 38, wherein at least one of said first chemical and said second chemical includes at least one of Ne, Ar, Kr and Xe.

40. The system of claim 36, wherein:

said at least one transducer comprises (i) a first transducer on said first container wall that is adjacent to and extends toward said thin sheet and (ii) a second transducer on a second container wall that is spaced apart from and faces said first container wall; and

the first and second transducers are activated at respective first and second activation levels so that a concentration of said acoustic cavities generated in said removal liquid is approximately uniform along a line segment extending between said first container wall and the second container wall.

41. The system of claim 40, wherein said first transducer and said second transducer are configured so that (1) said concentration of said acoustic cavities generated by said first transducer decreases approximately monotonically as a location on said line segment moves from said first container wall toward a center of said line segment and (2) said concentration of said acoustic cavities generated by said second transducer decreases approximately monotonically as a location on said line segment moves from said second container wall toward the center of said line segment.

42. The system of claim 41, further comprising (iii) a third transducer on said first container wall, adjacent to said first transducer and extending toward said thin sheet and (iv) a fourth transducer on said second container wall, adjacent to said second transducer and extending toward said thin sheet, where the third and fourth transducers are configured so that (3) concentration of said acoustic cavities generated by said third transducer increases approximately monotonically as a location on said line segment moves from said first container wall toward said center of said line segment and (4) concentration of said acoustic cavities generated by said fourth transducer increases approximately monotonically as a location on said line segment moves from said second container wall toward said center of said line segment.

42A. The system of claim 41, wherein an acoustic field generated by at least one of said first transducer and said second transducer is caused to rotate with passage of time in a plane containing said line segment that extends between said first container wall and the second container wall so that said concentration of said acoustic cavities generated in said particle removal liquid varies with the passage of time.

42B. The system of claim 41, wherein said concentration of said acoustic cavities generated by at least one of said first transducer and said second transducer is non-uniform along at least one second line segment within said particle removal liquid that extends substantially parallel to at least one of said first container wall and said second container wall.

43. The system of claim 40, wherein said first transducer and said second transducer are configured so that (1) said concentration of said acoustic cavities generated by said first transducer increases approximately monotonically as a location on said line segment moves from said first container wall toward a center of said line segment and (2) said concentration of said acoustic cavities generated by said second transducer increases approximately monotonically as a location on said line segment moves from said second container wall toward the center of said line segment.

44. The system of claim 40, wherein said first transducer and said second transducer are configured so that said concentration of said acoustic cavities generated in said particle removal liquid is approximately equal to $a + b \cdot \cosh\{\alpha(x-L/2)\}$, where a, b and α are selected constants with b and α positive, x is a location coordinate measured in a direction extending between said first and second container walls, and L is a distance of separation between said first and second container walls.

45. The system of claim 40, wherein said first transducer and said second transducer are configured so that said concentration of said acoustic cavities generated in said particle removal liquid is approximately proportional to $a + c \cdot \exp\{-\beta^2(x-L/2)^2\}$, where a, c and β are constants, with c and β positive, x is a location coordinate measured in a direction extending between said first and second container walls, and L is a distance of separation between said first and second container walls.

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46. The system of claim 40, wherein said first transducer and said second transducer are configured so that said concentration of said acoustic cavities generated in said particle removal liquid is approximately proportional to $a + b\cdot\cosh\{\alpha(x-L/2)\} + c\cdot\exp\{-\beta^2(x-L/2)^2\}$, where a, b, c, α and β are constants, with b, c, α and β positive, x is a location coordinate measured in a direction extending between said first and second container walls, and L is a distance of separation between said first and second container walls.

46A. The system of claim 43, wherein an acoustic field generated by at least one of said first transducer and said second transducer is caused to rotate with passage of time in a plane containing said line segment that extends between said first container wall and the second container wall so that said concentration of said acoustic cavities generated in said particle removal liquid varies with the passage of time.

47. The system of claim 40, further comprising selecting said particle removal liquid and said test liquid to be substantially the same liquid.

48. The system of claim 40, wherein said particle removal liquid is selected from the group of liquids consisting of H_2O, NH_3, H_2O_2, H_2SO_4 and O_3 dissolved in water.

49. The system of claim 40, wherein said test liquid is selected from the group of liquids consisting of DI water and DI water plus an inert fluid drawn from Ne and Ar.

50. The system of claim 40, wherein said at least one transducer is configured to emit a first signal having a first selected output frequency or, alternatively, to emit a second signal having a second selected output frequency,

respectively, in said particle removal liquid, where each of the first and second output frequencies is in a range 100-3000 KHz.

51. A method for removal of one or more particles attached to a solid surface, the method comprising:

immersing at least a portion of a solid surface, having at least one particle attached thereto that is to be removed from the surface, in a selected particle removal liquid container in a liquid container;

positioning an assembly of two or more activatable transducers in contact with at least one of the removal liquid and the container, where each transducer is capable of generating at least one cavity in the removal liquid and where the generated cavity subsequently collapses and provides a mechanism for removal of the at least one particle attached to a solid surface suspended in the particle removal liquid;

introducing a selected concentration of a selected cavity enhancement liquid into the removal liquid;

activating the transducers to a selected energy level to initially generate a plurality of cavities within the combined removal liquid and cavity enhancement liquid;

when a selected density of cavities is established in the removal liquid, reducing at least one of (i) the concentration of the cavity enhancement liquid to a selected reduced concentration level and (ii) the activation energy of the transducers to a selected reduced activation energy.

52. A system for removal of one or more particles attached to a solid surface, the system comprising:

a liquid container containing a selected particle removal liquid and configured to receive at least a portion of a solid surface, having at least one particle attached thereto that is to be removed from the surface;

an assembly of two or more activatable transducers, positioned in contact with at least one of the removal liquid and the container, where each transducer is capable of generating at least one cavity in the removal liquid, where the generated cavity subsequently collapses and provides a mechanism for removal of the at least one particle attached to a solid surface suspended in the particle removal liquid, and where the removal liquid initially includes a selected concentration of a selected cavity enhancement liquid;

a controllable transducer activation mechanism to activate the transducers to a selected energy level to initially generate a plurality of cavities within the combined removal liquid and cavity enhancement liquid, wherein, when a selected density of cavities is established in the removal liquid, at least one of the following actions is taken: (i) the concentration of the cavity enhancement liquid is reduced to a selected reduced concentration level and (ii) the activation energy of the transducers is reduced to a selected reduced activation energy.

53. A method for removal of one or more particles attached to a solid surface, the method comprising:

immersing at least a portion of a solid surface, having at least one particle attached thereto that is to be removed from the surface, in a selected particle removal liquid container in a liquid container;

positioning at least first, second and third activatable transducers in contact with at least one of the removal liquid and the container, where each transducer is capable of generating at least one cavity in the removal liquid and where the generated cavity subsequently collapses and provides a mechanism for removal of the at least one particle attached to a solid surface suspended in the particle removal liquid;

activating the first, second and third transducers to selected first, second and third energy levels at selected first, second and third excitation frequencies and for first, second and third time intervals, respectively, to generate one or more cavities

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by each transducer within the removal liquid, where the first, second and third frequencies are not commensurate with each other; and

activating the first, second and third transducers to selected fourth, fifth and sixth energy levels at selected fourth, fifth and sixth excitation frequencies and for fourth, fifth and sixth time intervals, respectively, to generate one or more cavities by each transducer within the removal liquid, where the fourth, fifth and sixth frequencies are not commensurate with each other, and the fourth, fifth and sixth time intervals follow the first, second and third time intervals, respectively.

53A. The method of claim 53, further comprising:

activating the first, second and third transducers to selected seventh, eighth and ninth energy levels at selected seventh, eighth and ninth excitation frequencies and for seventh, eighth and ninth time intervals, respectively, to generate one or more cavities by each transducer within the removal liquid, where said first and fourth frequencies and the seventh frequency are part of a substantially continuous selected first range of frequencies, said second and fifth frequencies and the eighth frequency are part of a substantially continuous selected second range of frequencies, and said third and sixth frequencies and the ninth frequency are part of a substantially continuous selected third range of frequencies.

54. A system for removal of one or more particles attached to a solid surface, the system comprising:

a liquid container containing a selected particle removal liquid and configured to receive at least a portion of a solid surface, having at least one particle attached thereto that is to be removed from the surface;

an assembly of first, second and third activatable transducers, positioned in contact with at least one of the removal liquid and the container, where each transducer is capable of generating at least one cavity in the removal liquid, where the generated cavity subsequently collapses and provides a mechanism for removal of the at least one particle attached to a solid surface suspended in the

particle removal liquid, where the first, second and third frequencies are not commensurate with each other;

a controllable transducer activation mechanism to activate the first, second and third transducers to selected first, second and third energy levels at selected first, second and third activation frequencies and for first, second and third time intervals, respectively, to generate a plurality of cavities within the removal liquid, and to activate the first, second and third transducers to selected fourth, fifth and sixth energy levels at selected fourth, fifth and sixth activation frequencies and for fourth, fifth and sixth time intervals, respectively, to generate another plurality of cavities within the removal liquid, where the first, second and third frequencies are not commensurate with each other.

54A. The system of claim 54, wherein said transducer activation mechanism activates the first, second and third transducers to selected seventh, eighth and ninth energy levels at selected seventh, eighth and ninth excitation frequencies and for seventh, eighth and ninth time intervals, respectively, to generate one or more cavities by each transducer within the removal liquid, where said first and fourth frequencies and the seventh frequency are part of a substantially continuous selected first range of frequencies, said second and fifth frequencies and the eighth frequency are part of a substantially continuous selected second range of frequencies, and said third and sixth frequencies and the ninth frequency are part of a substantially continuous selected third range of frequencies.

55. A method for removal of one or more particles attached to a solid surface, the method comprising:

providing a liquid container with a selected particle removal liquid, where the container has at least one container wall that includes an array of at least one activatable transducer capable of generating acoustical cavities in the removal liquid;

positioning an array of at least two spaced apart acoustical cavity sensors within the removal liquid, spaced apart from the container wall that includes the at least one transducer;

activating the at least one transducer to generate an array of acoustical cavities in the removal liquid, and determining a time average of a distribution of cavities $D(x,y;avg)$ produced at I selected locations (I   2), $(x,y) = \{(x_i,y_i)\}_i$ between the at least one transducer and the at least two cavity sensors;

comparing the time averaged distribution of cavities sensed at the selected locations with a reference distribution of cavities $D(x,y;ref)$ at corresponding locations; and

when the time averaged distribution of cavities differs from the reference distribution of cavities by more than a threshold amount at the selected locations, interpreting this condition as indicating that the array of transducers is not performing acceptably.

56. The method of claim 55, further comprising:

when said time averaged distribution of cavities differs from said reference distribution of cavities by no more than said threshold amount at said selected locations, interpreting this condition as indicating that said array of transducers is performing acceptably.

57. The method of claim 55, wherein an extent by which said time averaged distribution of cavities $D(x,y;avg)$ differs from said reference distribution of cavities $D(x,y;ref)$ is determined by a process comprising:

forming a selected combination $C\{D(x,y;avg),D(x,y;ref)\}$, where the combination is homogeneous with a selected degree of homogeneity β (0) in said time averaged distribution and said reference distribution at said selected locations, and the selected combination C satisfies $C\{D(x,y;test),D(x,y;test)\} = 0$ for an arbitrary test distribution $D(x,y;test)$ of said cavities, defined at said selected locations.

58. The method of claim 57, further comprising choosing said selected combination C of said time averaged distribution of cavities and said reference distribution of cavities to be

$$C\{D(x,y;avg),D(x,y;ref)\} = \{\sum_{i=1}^{I} w_i\, |D(x_i,y_i;avg) - D(x_i,y_i;ref)|^{\mu}\}^{1/\mu},$$

where $\{w_i\}_i$ is a sequence of selected non-negative weight coefficients, whose sum equals 1, and μ is a selected positive constant.

59. The method of claim 57, further comprising choosing said selected combination C of said time averaged distribution of cavities and said reference distribution of cavities to be

$$C\{D(x,y;avg),D(x,y;ref)\} = \{\sum_{i=1}^{I} w_i\, |D(x_i,y_i;avg)/D(x_i,y_i;ref) - 1|^{\mu}\}^{1/\mu},$$

where $\{w_i\}_i$ is a sequence of selected non-negative weight coefficients, whose sum equals 1, and μ is a selected non-zero constant.

60. The method of claim 57, further comprising determining if said time averaged distribution differs from said reference distribution by more than said threshold amount by determining if $C\{D(x,y;avg),D(x,y;ref)\}$ is greater than a selected threshold value C_{thr}.

61. The method of claim 57, further comprising choosing said selected combination C of said time averaged distribution of cavities and said reference distribution of cavities to be

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$$C\{D(x,y;avg),D(x,y;ref)\} = \{\sum_{i=1}^{I} w_i \,|D(x_i,y_i;avg)/D(x_i,y_i;ref)|^{\mu}\}^{1/\mu},$$

where $\{w_i\}_i$ is a sequence of selected non-negative weight coefficients, whose sum equals 1, and μ is a selected non-zero constant.

62. The method of claim 57, further comprising determining if said time averaged distribution differs from said reference distribution by more than said threshold amount by determining if $C\{D(x,y;avg),D(x,y;ref)\}$ is less than a selected threshold value C_{thr}.

63. A system for removal of one or more particles attached to a solid surface, the system comprising:

an array of at least two acoustical cavity sensors, spaced apart from a surface that includes at least one transducer in a particle removal liquid;

a transducer testing mechanism to activate the at least one transducer to generate an array of acoustical cavities in the removal liquid, and to determine a time average of a distribution of cavities $D(x,y;avg)$ produced at I selected locations (I 2), $(x,y) = \{(x_i,y_i)\}_i$ $(i = 1, \ldots, I)$ between the at least one transducer and the at least two cavity sensors; and

a comparison mechanism to compare the time averaged distribution of cavities sensed at the selected locations with a reference distribution of cavities $D(x,y;ref)$ at corresponding locations so that, when the time averaged distribution of cavities differs from the reference distribution of cavities by more than a threshold amount at the selected locations, the comparison mechanism interprets this condition as indicating that the array of transducers is not performing acceptably.

64. The system of claim 63, wherein, when said time averaged distribution of cavities differs from said reference distribution of cavities by no more than said

threshold amount at said selected locations, said comparison mechanism interprets this condition as indicating that said array of transducers is performing acceptably.

65. The system of claim 63, wherein said comparison mechanism determines an extent by which said time averaged distribution of cavities D(x,y;avg) differs from said reference distribution of cavities D(x,y;ref) by a process comprising:

forming a selected combination C{D(x,y;avg),D(x,y;ref)}, where the combination is homogeneous with a selected degree of homogeneity β (0) in said time averaged distribution and said reference distribution at said selected locations, and the selected combination C satisfies C{D(x,y;test),D(x,y;test)} = 0 for an arbitrary test distribution D(x,y;test) of said cavities, defined at said selected locations.

66. The system of claim 65, wherein said selected combination C of said time averaged distribution of cavities and said reference distribution of cavities is chosen to be

$$C\{D(x,y;avg),D(x,y;ref)\} = \{\sum_{i=1}^{I} w_i\,|D(x_i,y_i;avg) - D(x_i,y_i;ref)|^{\mu}\}^{1/\mu},$$

where $\{w_i\}_i$ is a sequence of selected non-negative weight coefficients, whose sum equals 1, and μ is a selected positive constant.

67. The system of claim 65, wherein said selected combination C of said time averaged distribution of cavities and said reference distribution of cavities is chosen to be

$$C\{D(x,y;avg),D(x,y;ref)\} = \{\sum_{i=1}^{I} w_i\,|D(x_i,y_i;avg)/D(x_i,y_i;ref) - 1|^{\mu}\}^{1/\mu},$$

where $\{w_i\}_i$ is a sequence of selected non-negative weight coefficients, whose sum equals 1, and μ is a selected non-zero constant.

68. The system of claim 65, wherein said comparison mechanism determines if said time averaged distribution differs from said reference distribution by more than said threshold amount by determining if $C\{D(x,y;avg),D(x,y;ref)\}$ is greater than a selected threshold value C_{thr}.

69. The system of claim 65, wherein said selected combination C of said time averaged distribution of cavities and said reference distribution of cavities is chosen to be

$$C\{D(x,y;avg),D(x,y;ref)\} = \{\sum_{i=1}^{I} w_i \, |D(x_i,y_i;avg)/D(x_i,y_i;ref)|^{\mu}\}^{1/\mu},$$

where $\{w_i\}_i$ is a sequence of selected non-negative weight coefficients, whose sum equals 1, and μ is a selected non-zero constant.

70. The system of claim 65, wherein said comparison mechanism determines if said time averaged distribution differs from said reference distribution by more than said threshold amount by determining if $C\{D(x,y;avg),D(x,y;ref)\}$ is less than a selected threshold value C_{thr}.

Abstract of the Invention

Methods and systems for providing, testing and maintaining a substantially uniform field of cavities, generated by an assembly of transducers in a particle removal (PR) liquid, to remove particles attached to a solid surface (e.g., a semiconductor wafer or chip) immersed in the PR liquid. Periodically, each transducer is adjusted so that a representative pre-implosion cavity diameter generated by that transducer lies in a selected range. Single surfaces or batches of surfaces can be cleaned. Methods and systems for promoting generation of an approximately uniform density of acoustic cavities are disclosed. Recapture and recycling of the PR liquid are available.

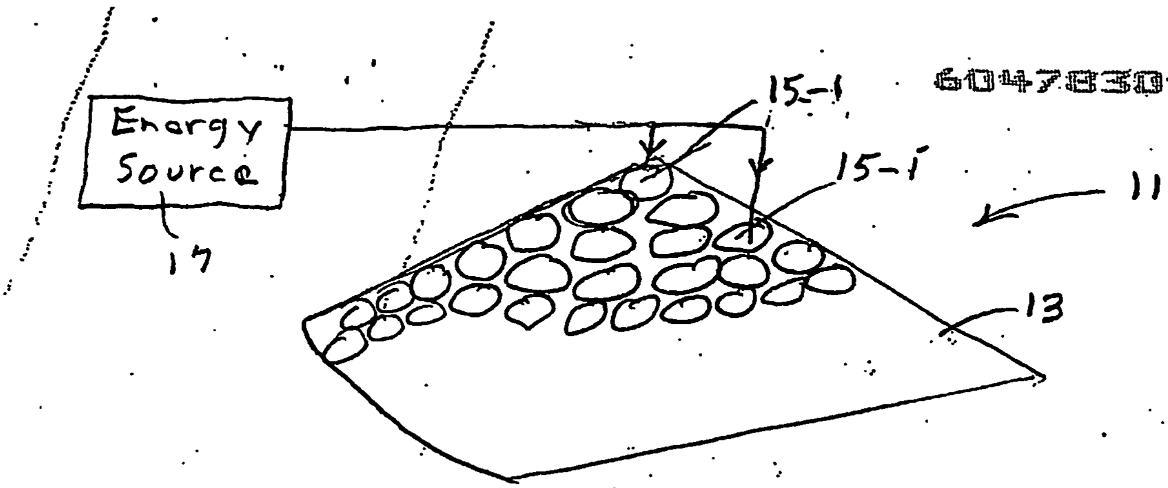

FIG. 1

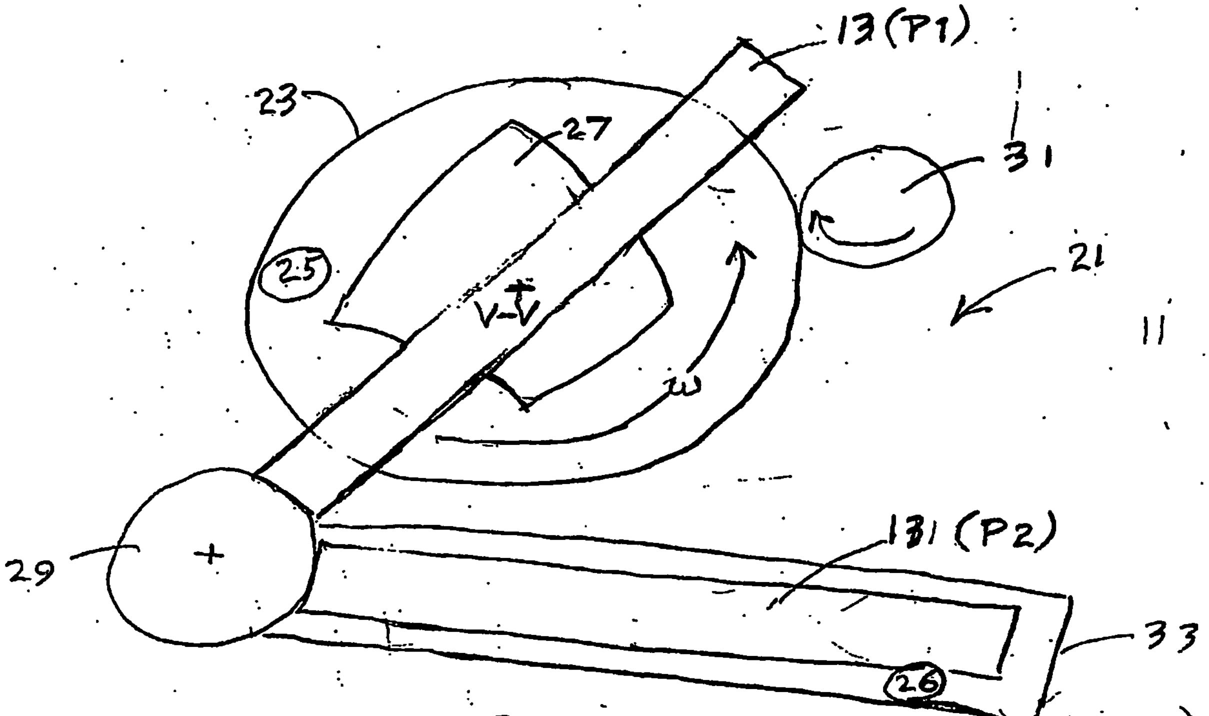

FIG. 2

[redacted]

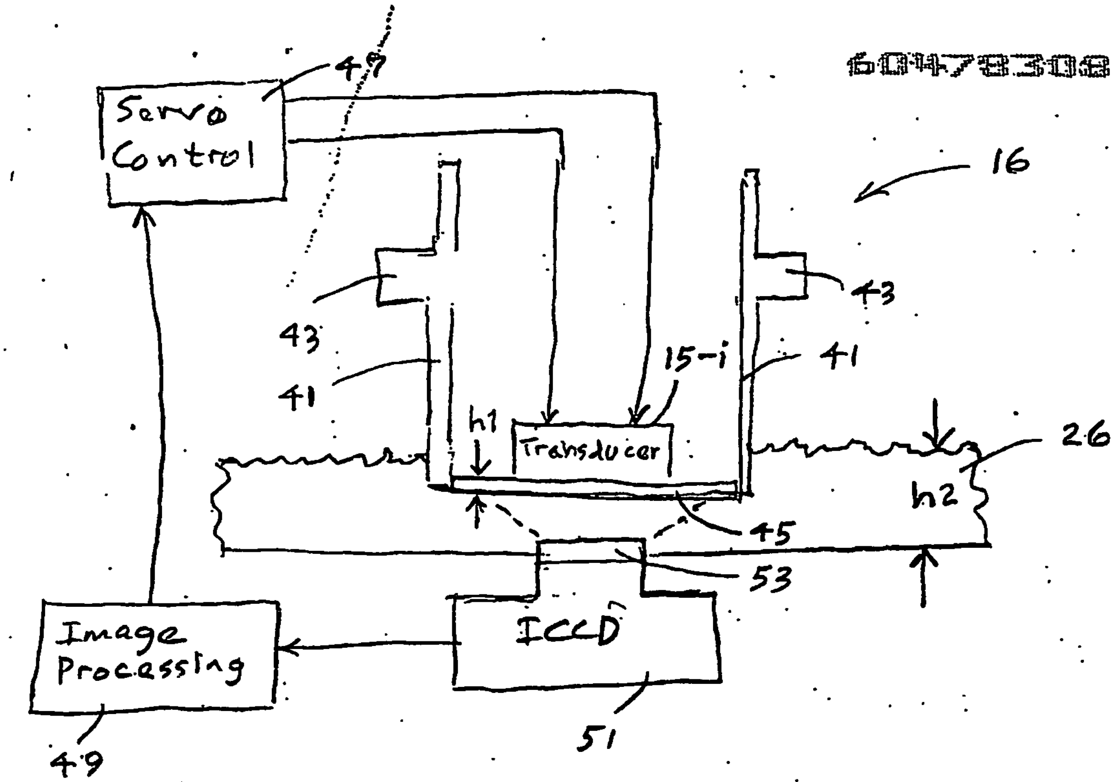
Servo Control
47
16
43
43
41
15-i
41
h1
Transducer
26
h2
45
53
Image Processing
ICCD
49
51

FIG. 3

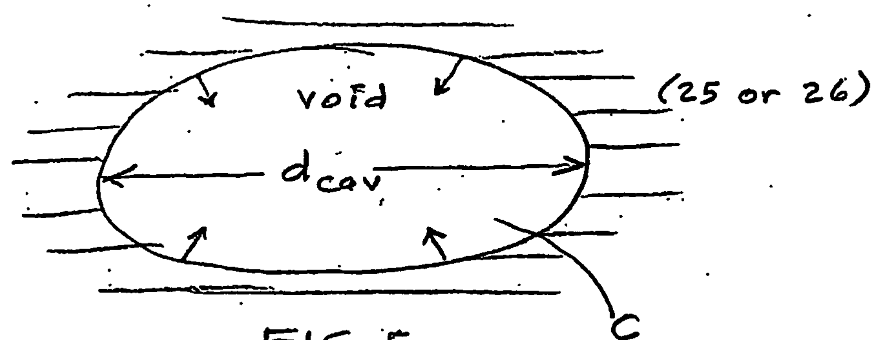
void
(25 or 26)
d_{cav}
C

FIG. 5

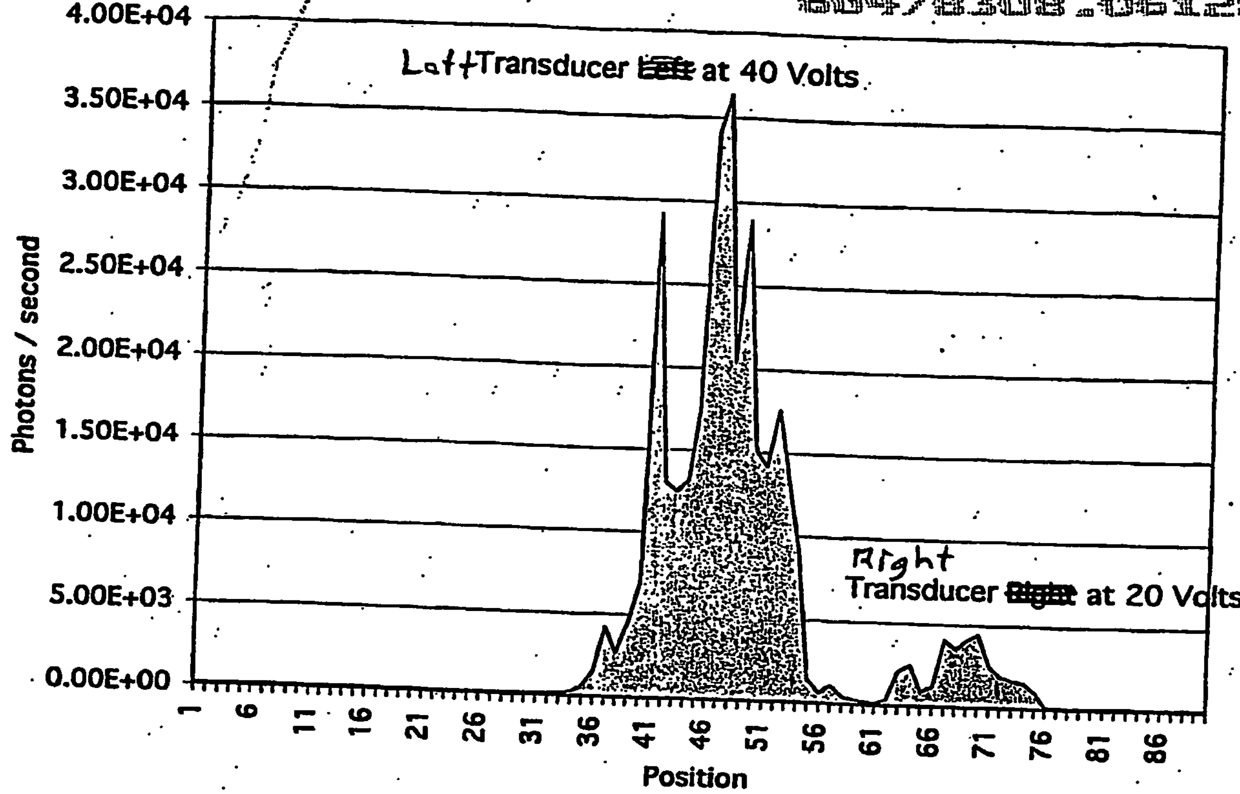
Left Transducer ~~Left~~ at 40 Volts
Right
Transducer ~~Right~~ at 20 Volts
Photons / second
4.00E+04
3.50E+04
3.00E+04
2.50E+04
2.00E+04
1.50E+04
1.00E+04
5.00E+03
0.00E+00
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 76 81 86
Position

FIG. 4B

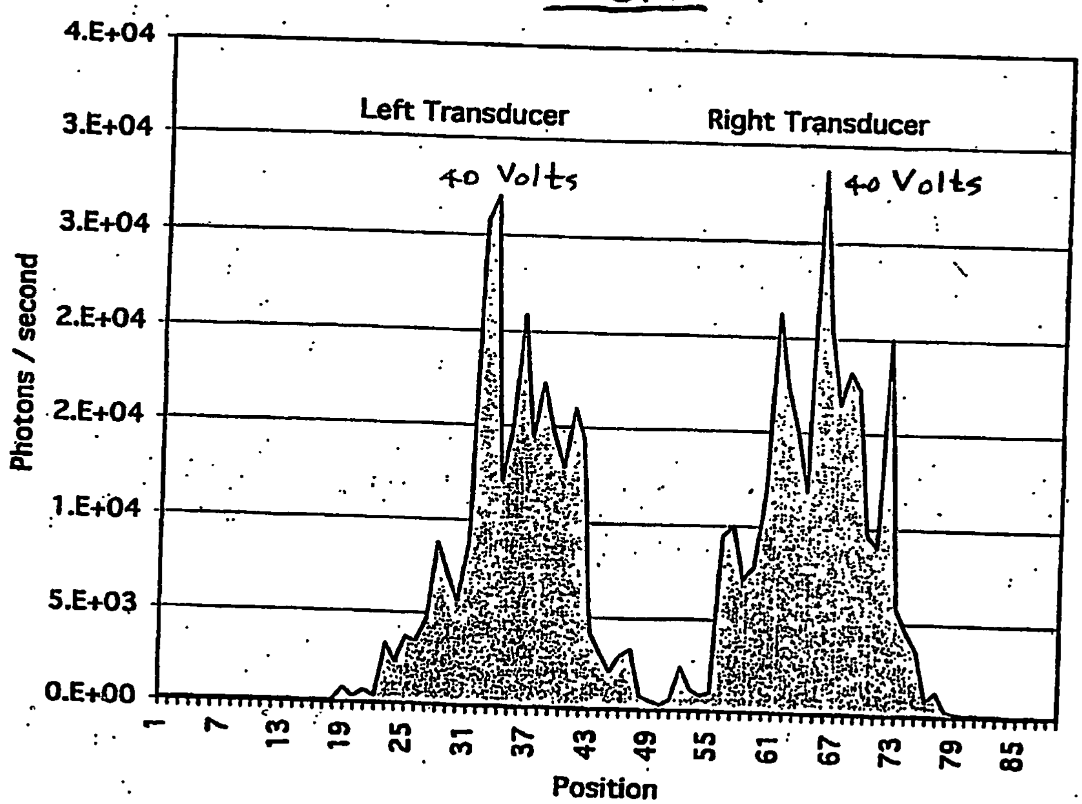
Left Transducer
Right Transducer
40 Volts
40 Volts
Photons / second
4.E+04
3.E+04
3.E+04
2.E+04
2.E+04
1.E+04
5.E+03
0.E+00
1 7 13 19 25 31 37 43 49 55 61 67 73 79 85
Position

FIG. 4A

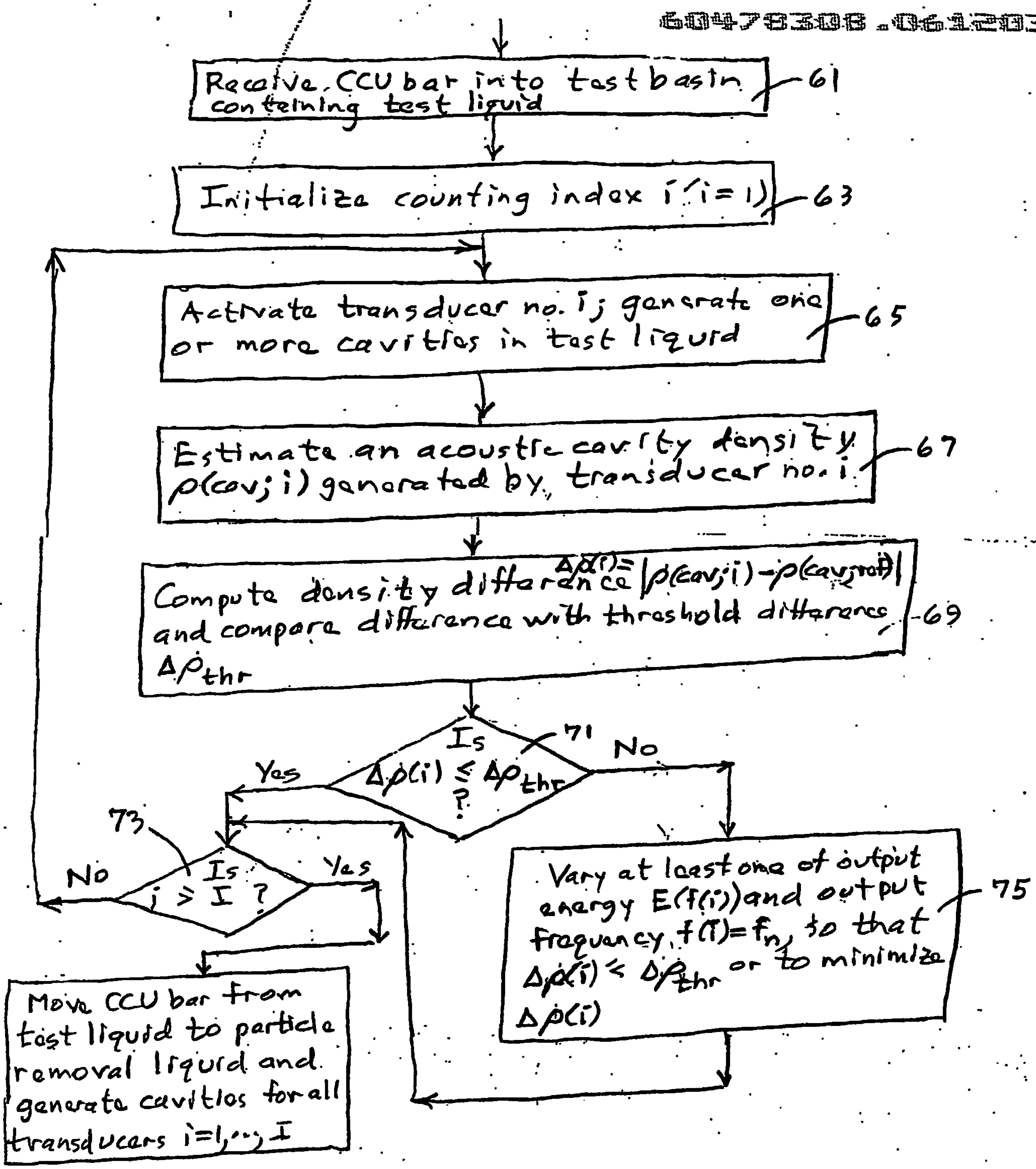
Receive CCU bar into test basin containing test liquid
61
Initialize counting index i (i=1)
63
Activate transducer no. i; generate one or more cavities in test liquid
65
Estimate an acoustic cavity density ρ(cav;i) generated by transducer no. i
67
Compute density difference Δρ(i)=|ρ(cav;i)−ρ(cav;ref)| and compare difference with threshold difference Δρthr
69
Is Δρ(i) ≤ Δρthr ?
71
Yes
No
73
Is i > I ?
No
Yes
Vary at least one of output energy E(f(i)) and output frequency f(i)=fn, so that Δρ(i) < Δρthr or to minimize Δρ(i)
75
Move CCU bar from test liquid to particle removal liquid and generate cavities for all transducers i=1,…,I

FIG. 6

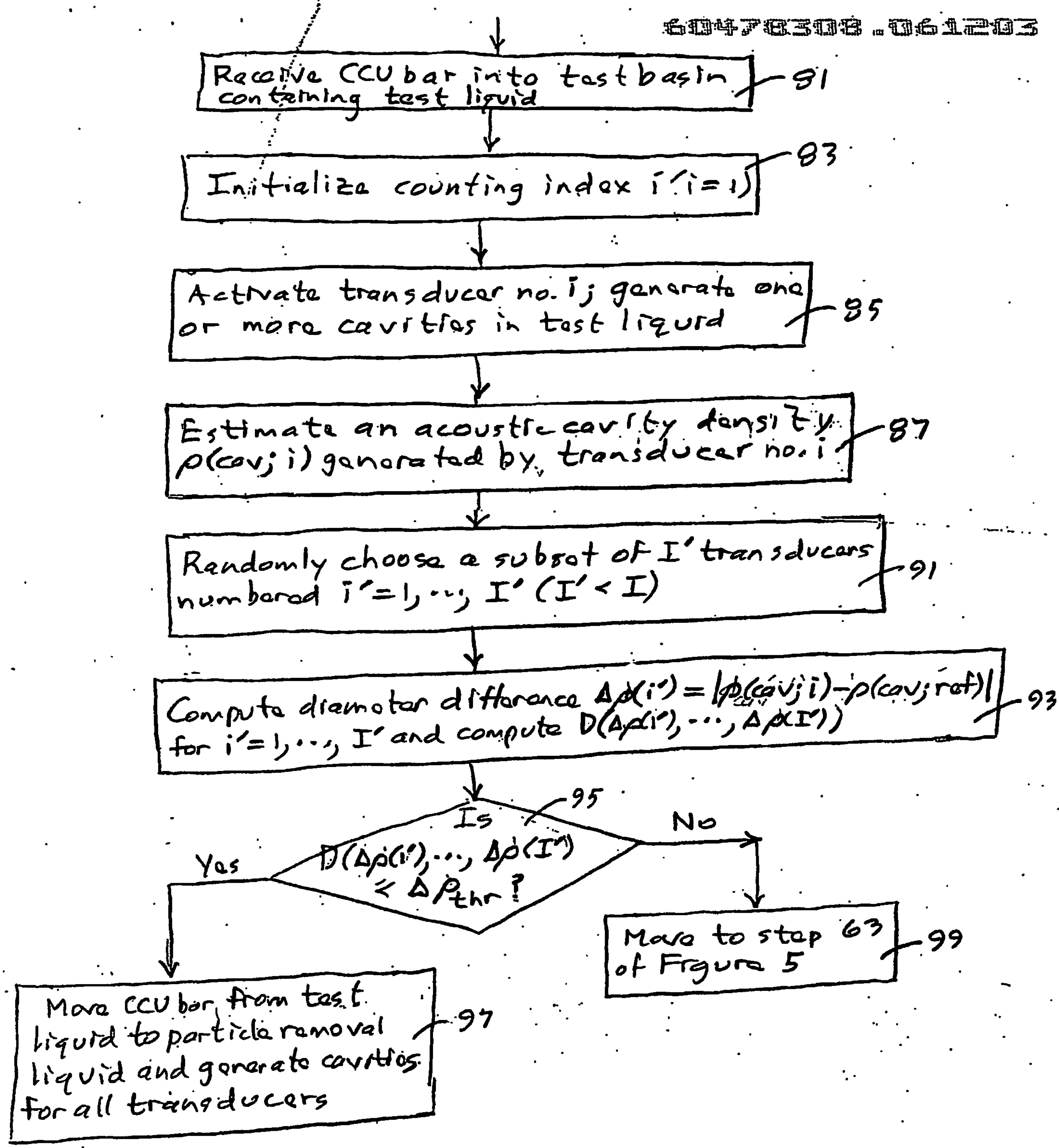
Receive CCU bar into test basin containing test liquid
81
Initialize counting index i (i=1)
83
Activate transducer no. i; generate one or more cavities in test liquid
85
Estimate an acoustic cavity density ρ(cav; i) generated by transducer no. i
87
Randomly choose a subset of I' transducers numbered i'=1, ..., I' (I' < I)
91
Compute diameter difference Δρ(i') = |ρ(cav; i) − ρ(cav; ref)| for i'=1, ..., I' and compute D(Δρ(i'), ..., Δρ(I'))
93
Is D(Δρ(i'), ..., Δρ(I')) ≤ Δρthr ?
95
Yes
No
Move CCU bar from test liquid to particle removal liquid and generate cavities for all transducers
97
Move to step 63 of Figure 5
99

FIG. 7

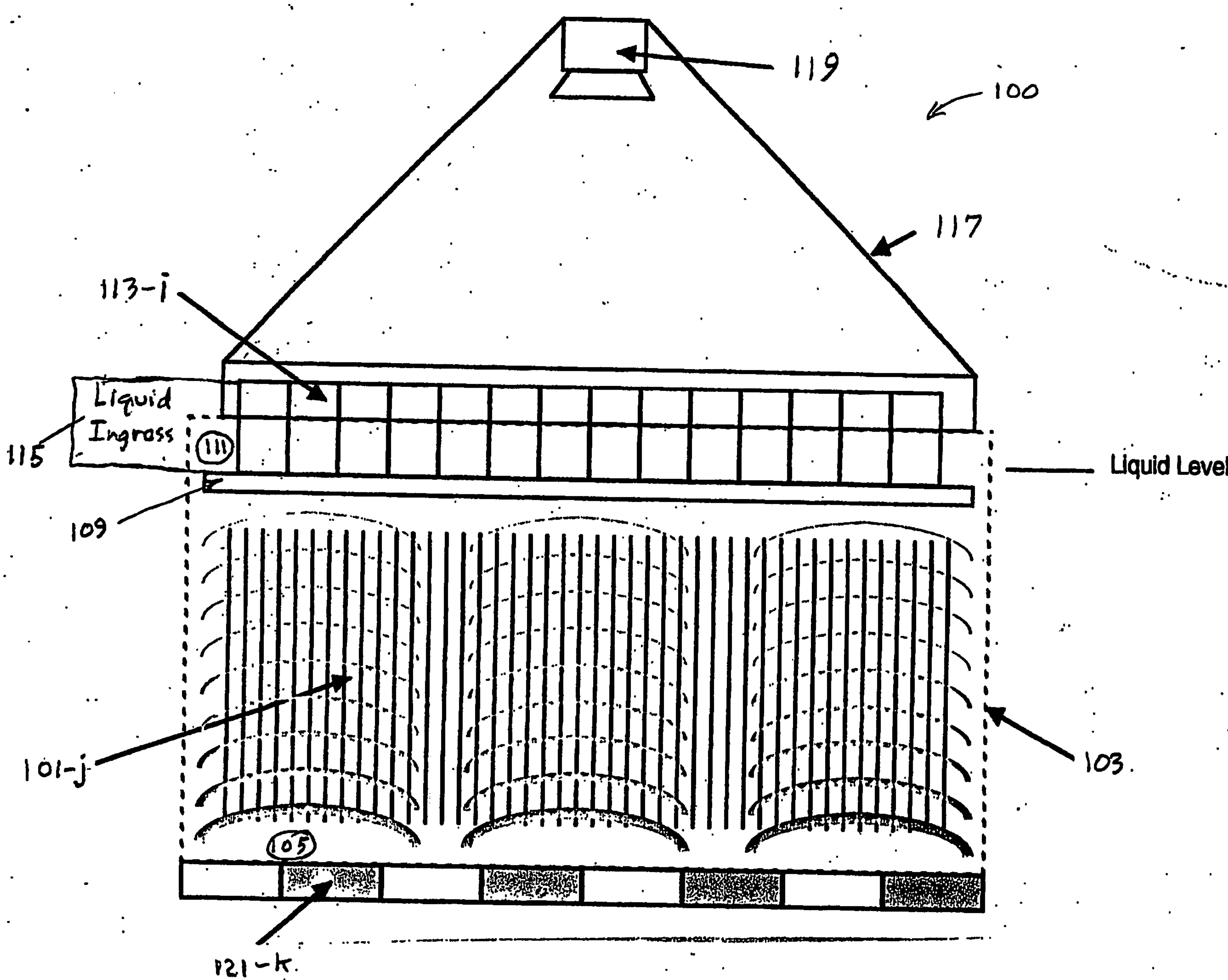
119
100
117
113-i
Liquid Ingress
111
115
Liquid Level
109
101-j
103
105
121-k

FIG. 8

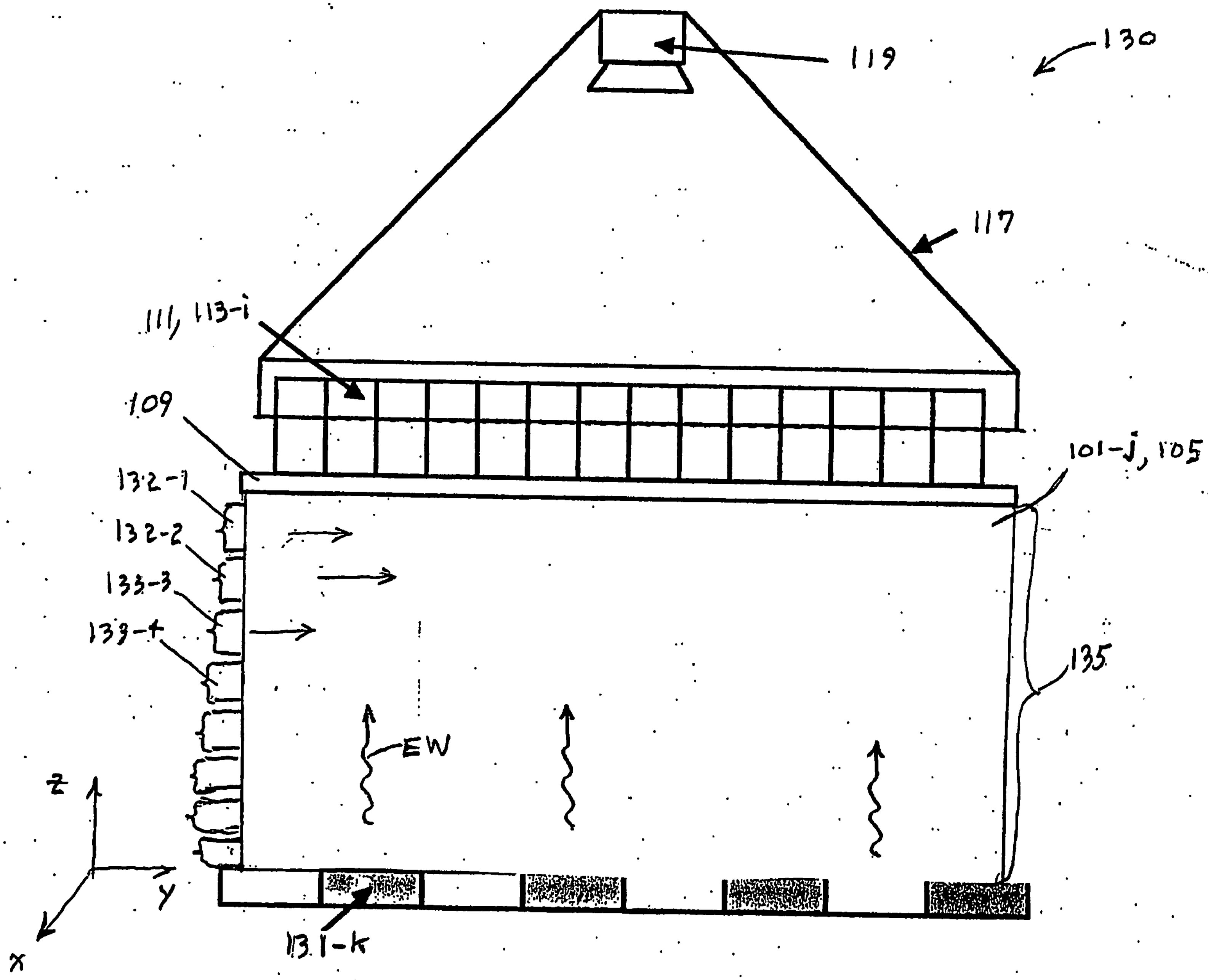
130
119
117
111, 113-i
109
101-j, 105
132-1
132-2
133-3
139-4
135
EW
131-k
z
y
x

FIG. 9

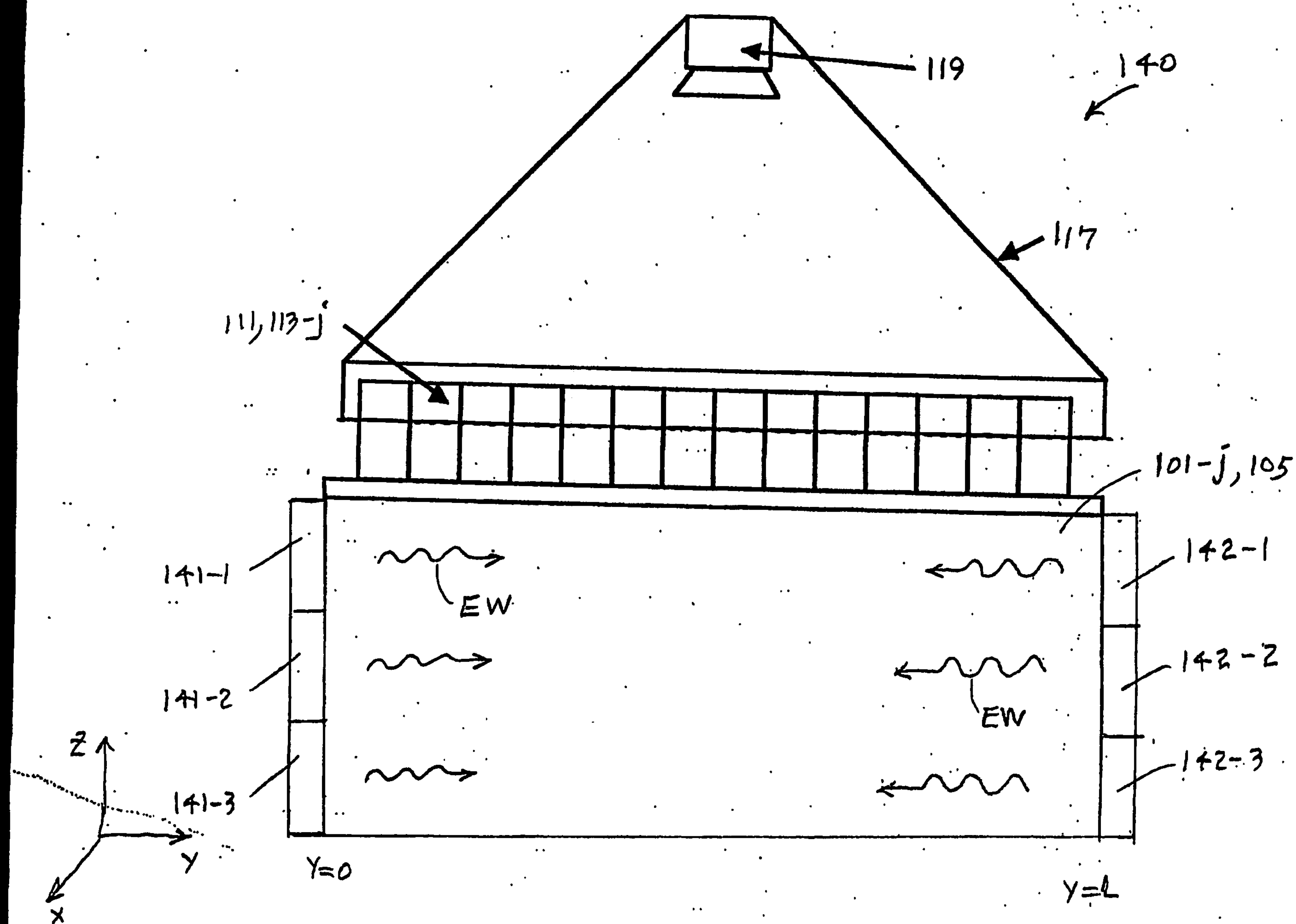
119
140
117
111, 113-j
101-j, 105
141-1
141-2
141-3
142-1
142-2
142-3
EW
EW
Z
Y
X
Y=0
Y=L

FIG. 10

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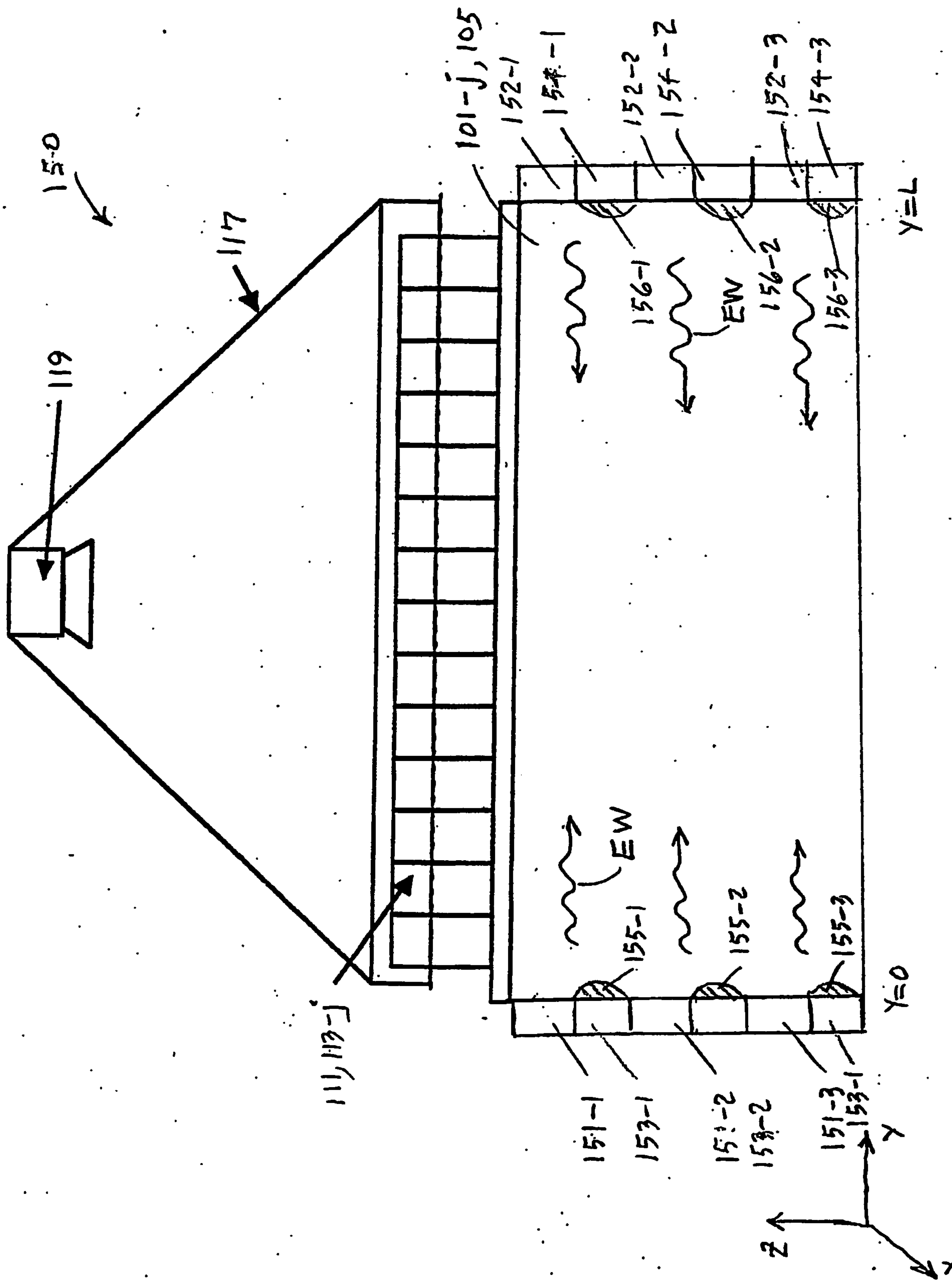


FIG. 11

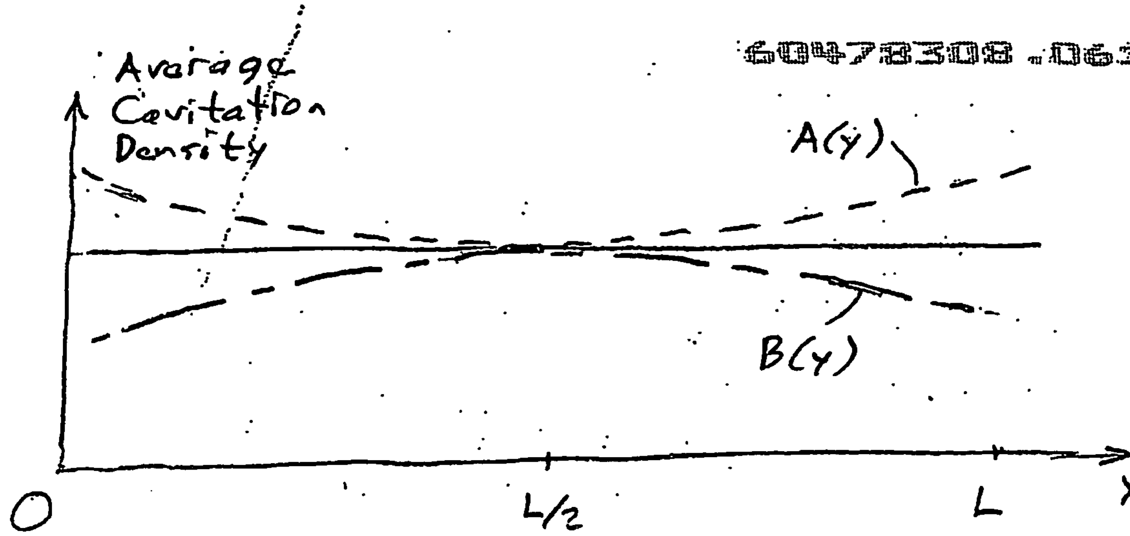


FIG. 12

60478308.061203

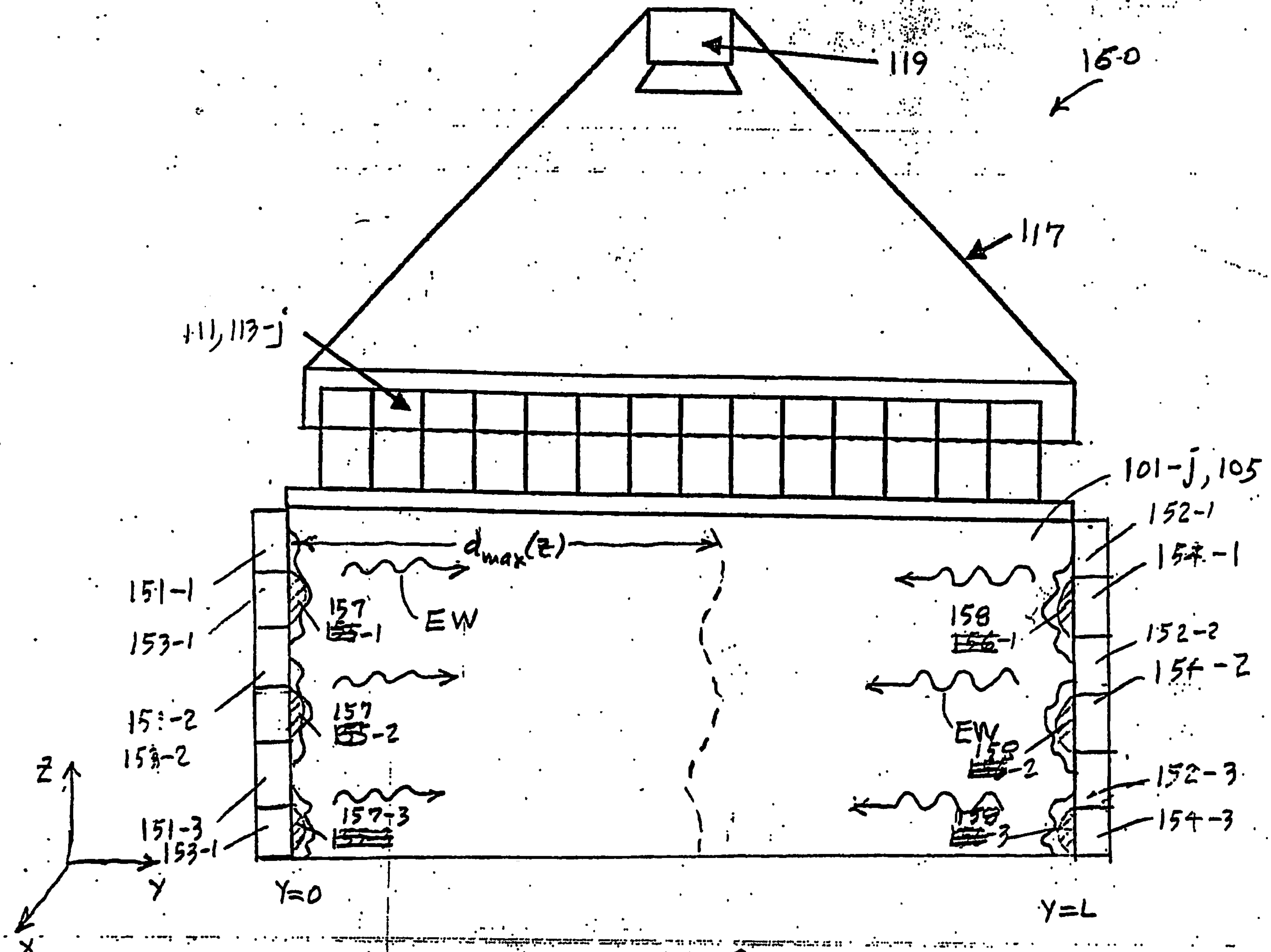


FIG. 13

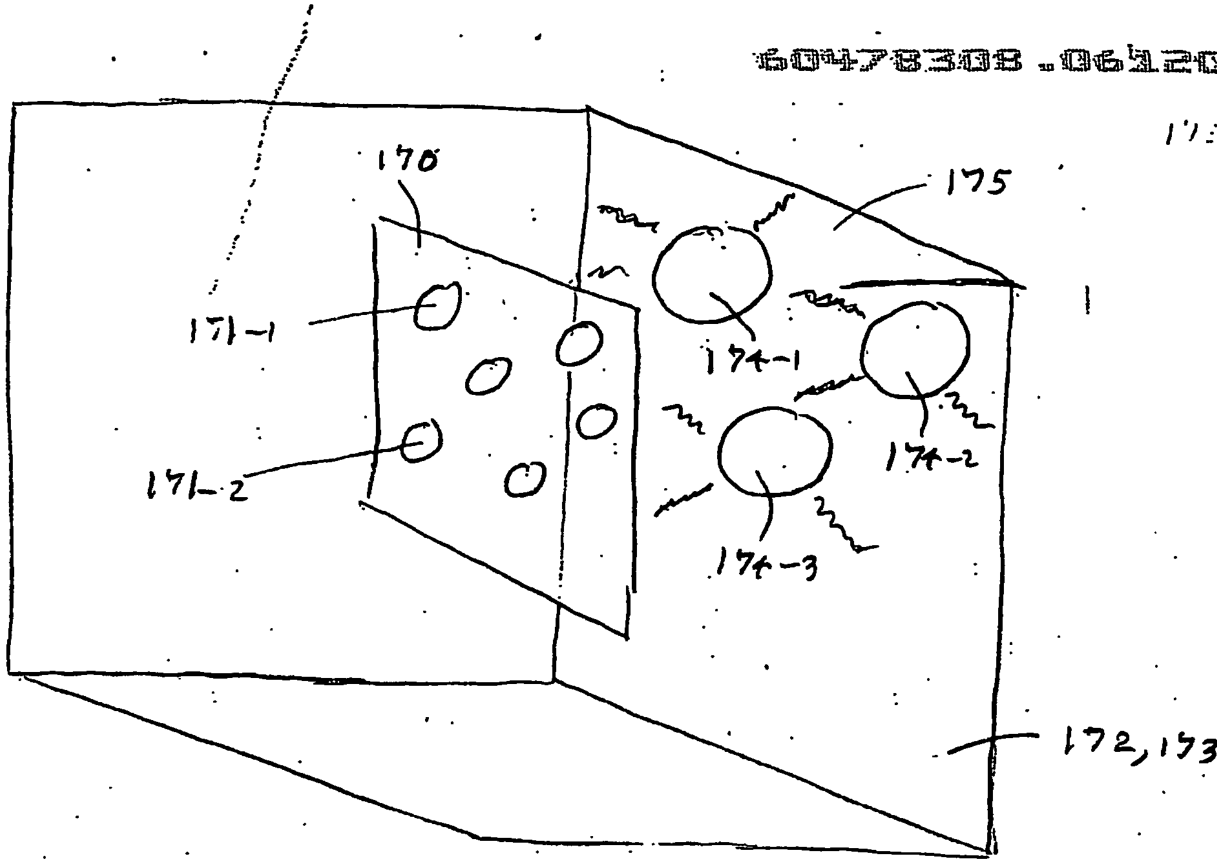


FIG. 14

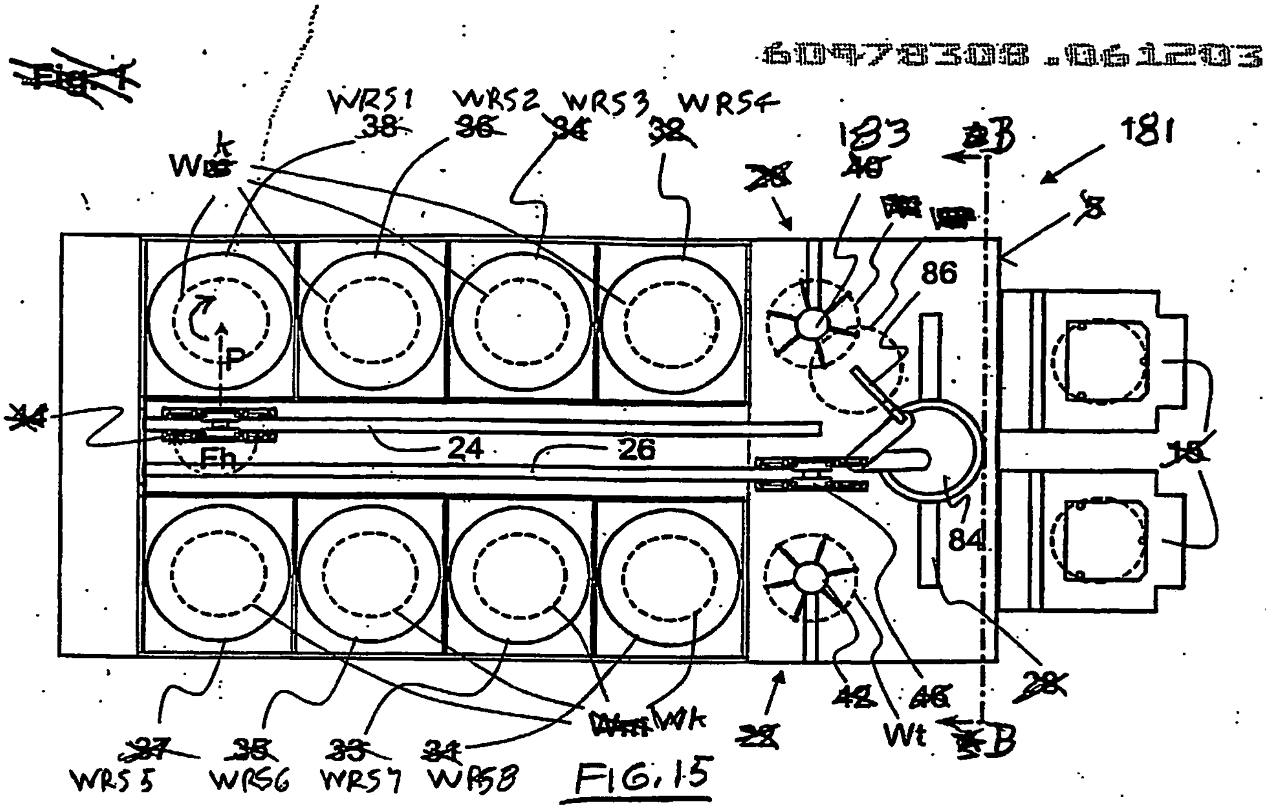

WRS1
WRS2
WRS3
WRS4
Wk
183
B
181
86
P
24
26
84
Fh
Wk
Wt
B
WRS5
WRS6
WRS7
WRS8

FIG. 15

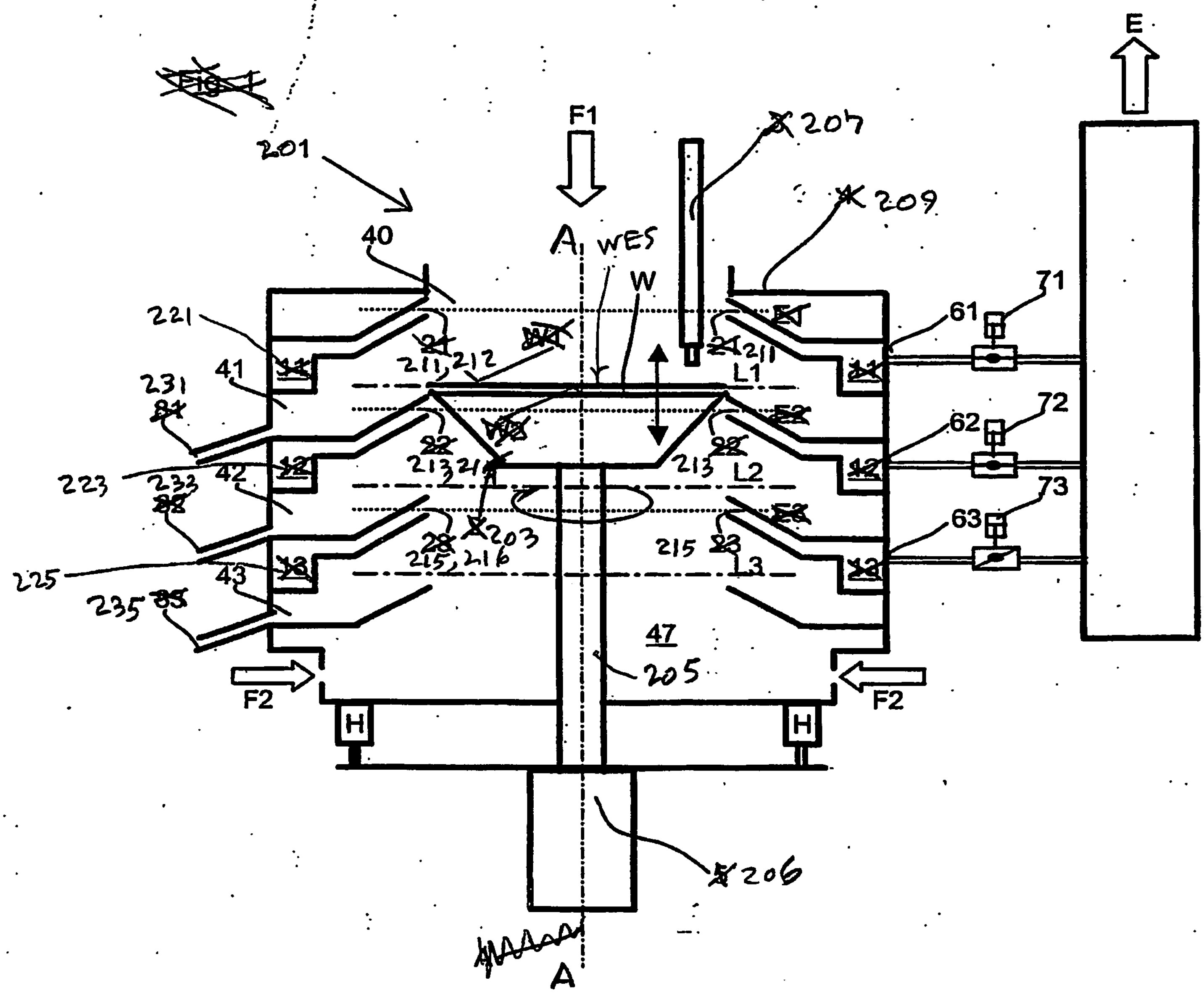
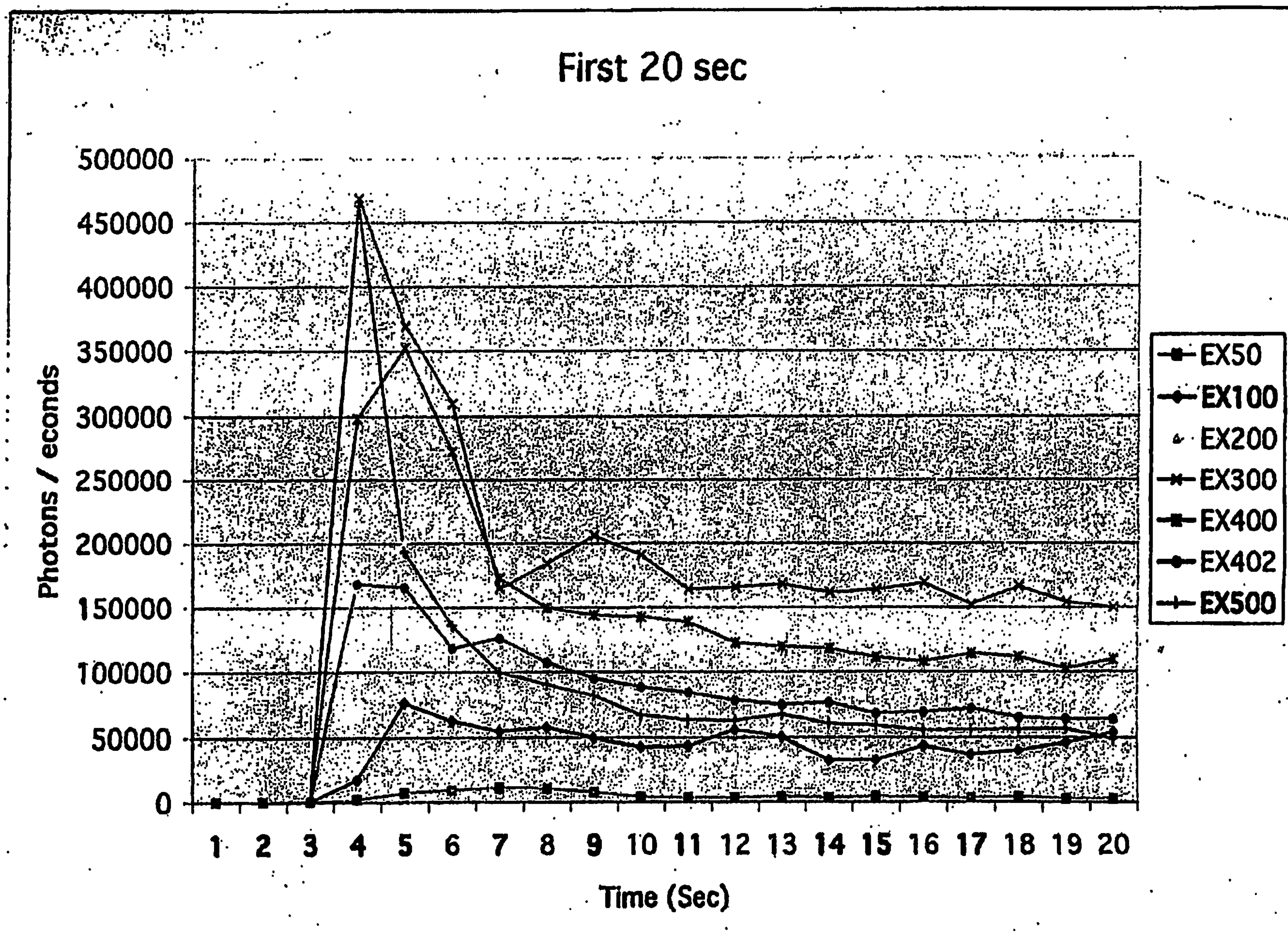

201
F1
207
209
E
A
WES
W
40
221
41
231
211,212
211
L1
61
71
223
233
42
213
214
213
L2
62
72
203
225
235
43
215,216
215
L3
63
73
47
205
F2
F2
H
H
206
A

FIG. 16



L TSUH

FIG. 17

60478308.061203

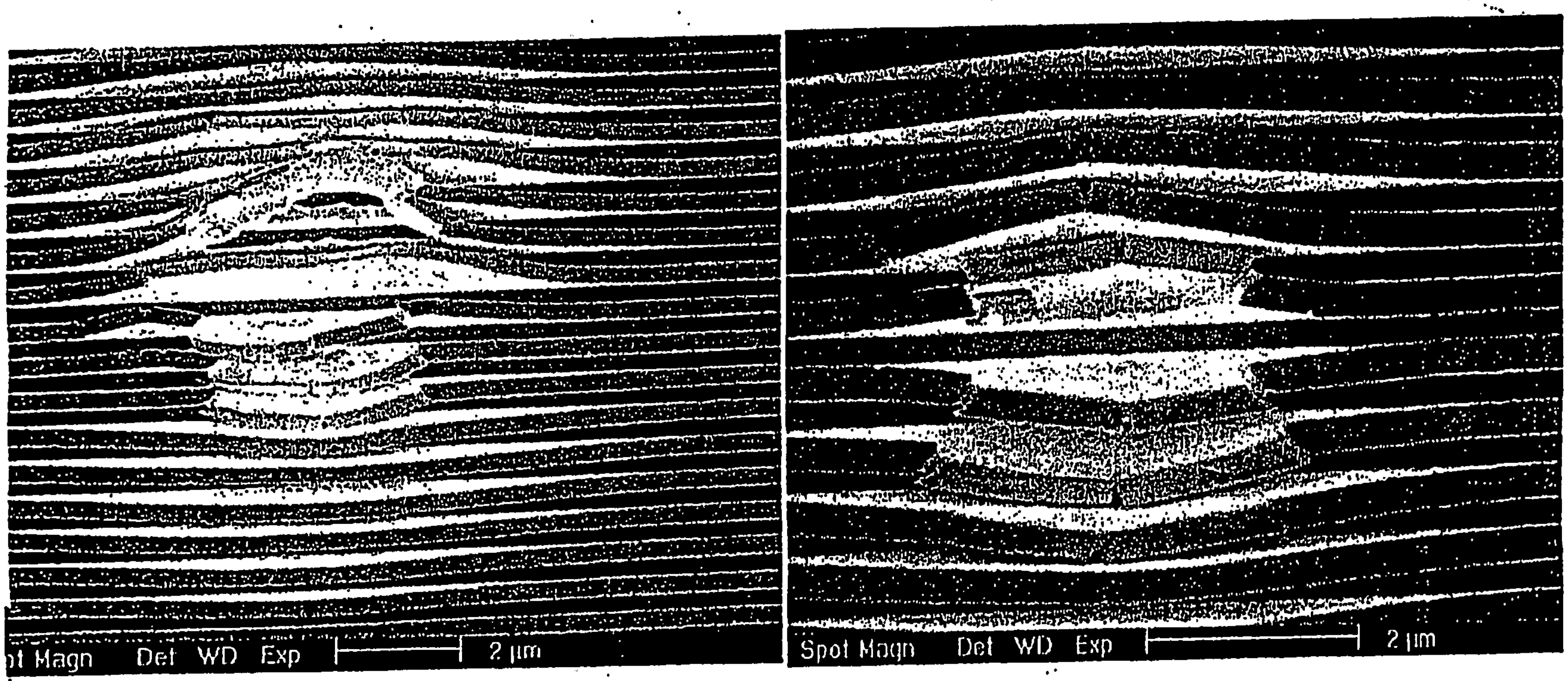


FIG 18

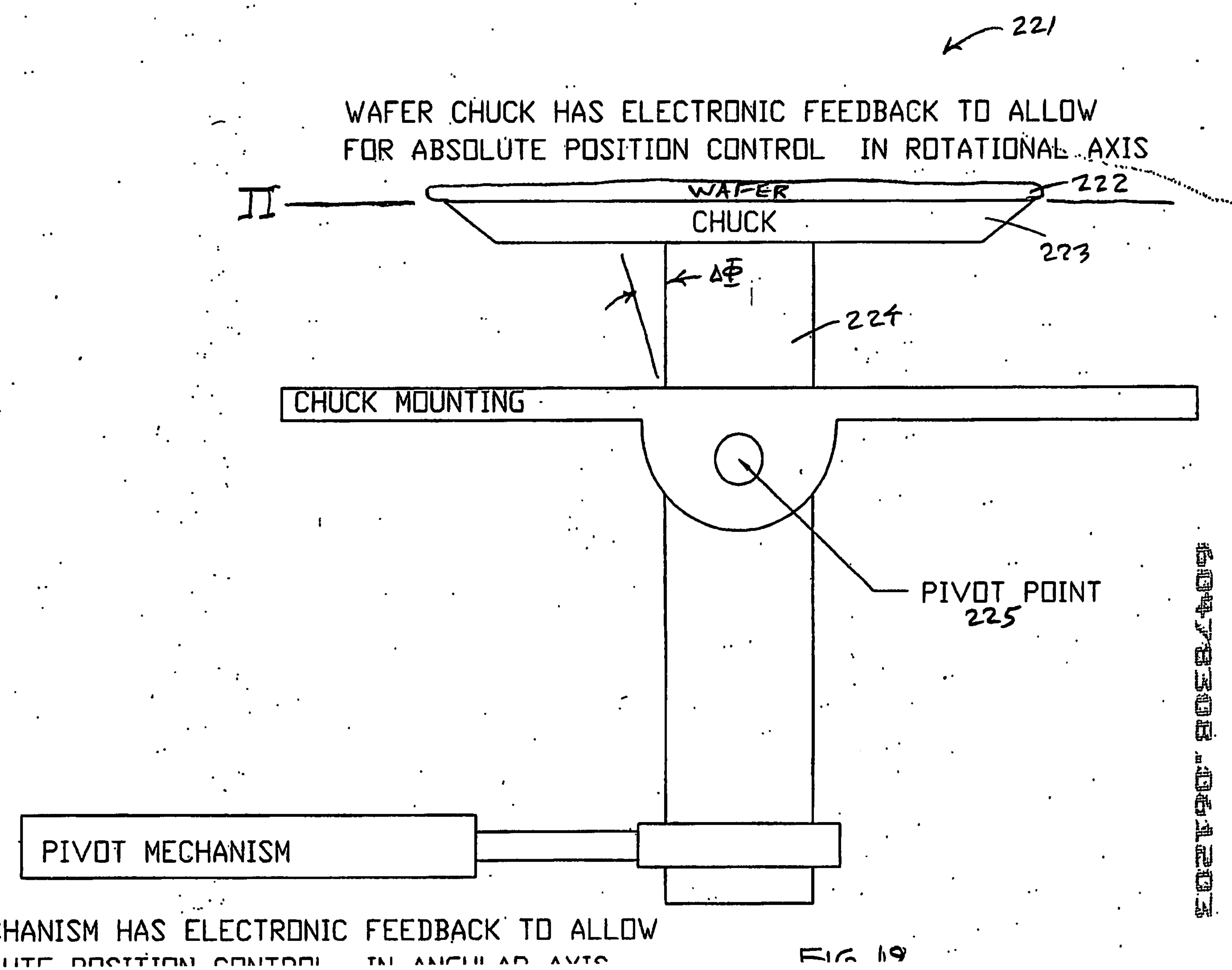


FIG 19

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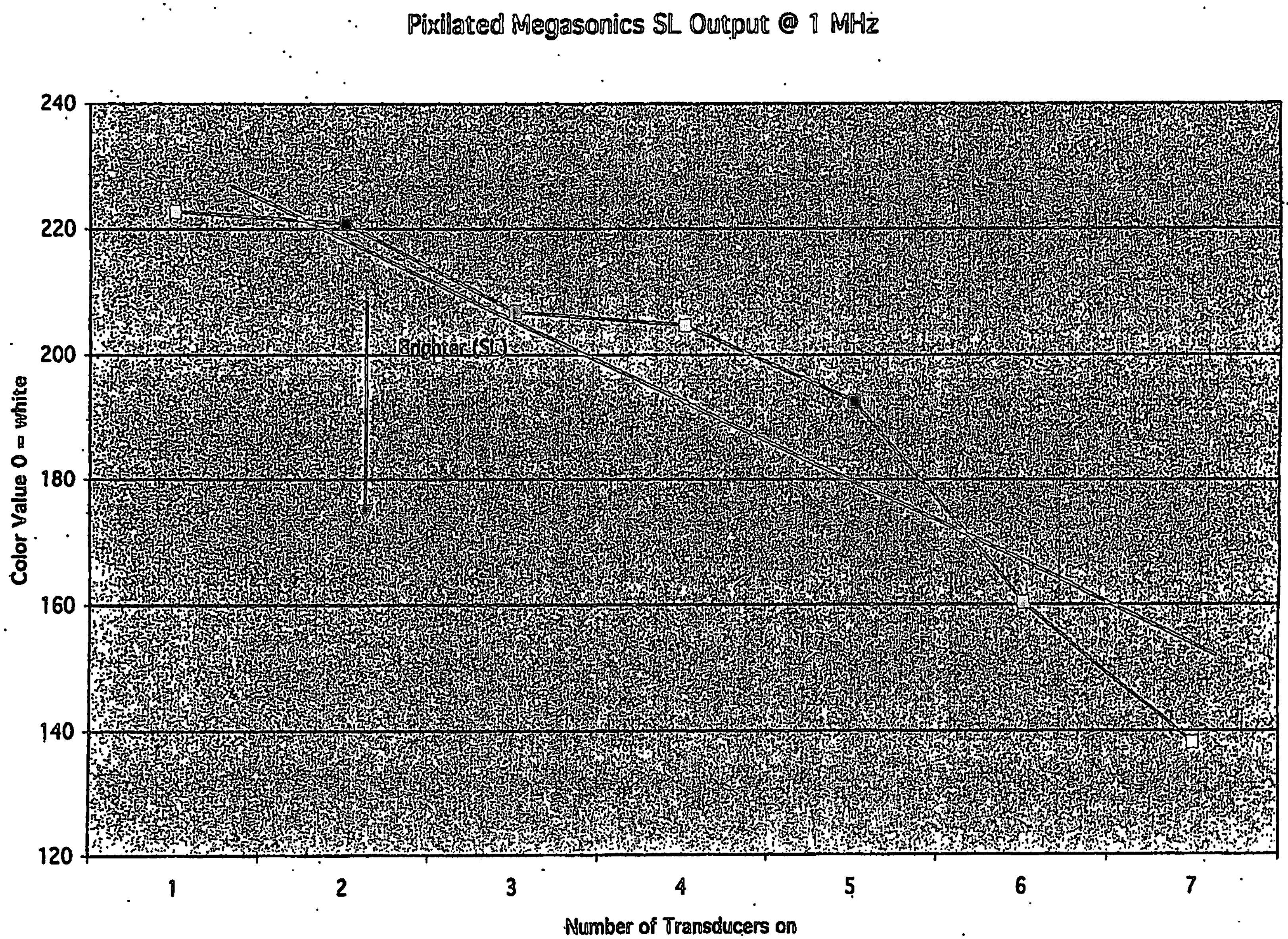

FIG. 20

~~Gary W. Ferrell SEZ America~~

~~CONFIDENTIAL~~

~~June 5, 2003~~

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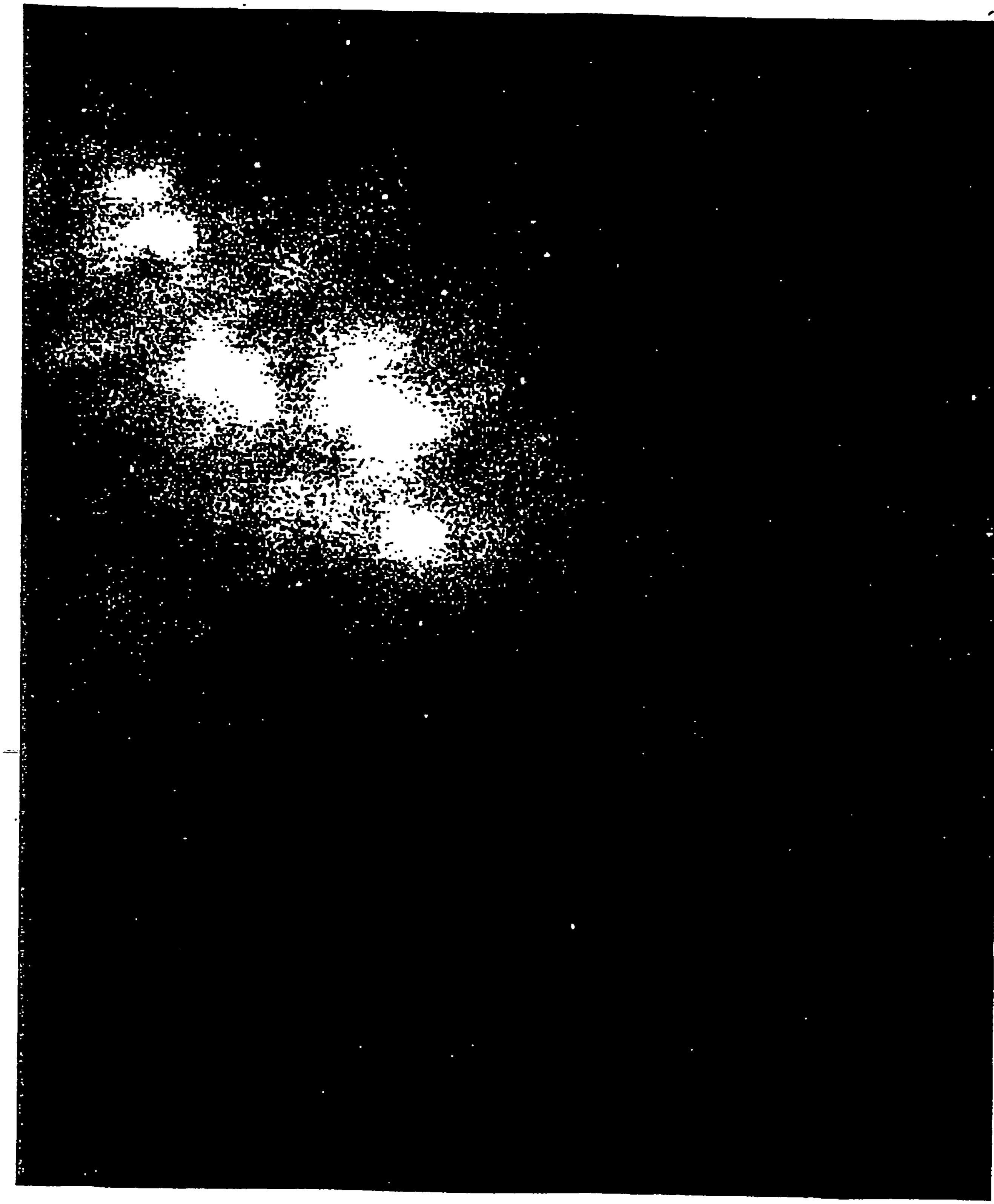

Time cleared 1.1.7 4 5 @ 4 V.

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Transducers 1,2,3,4,5,6,7 @ 4v

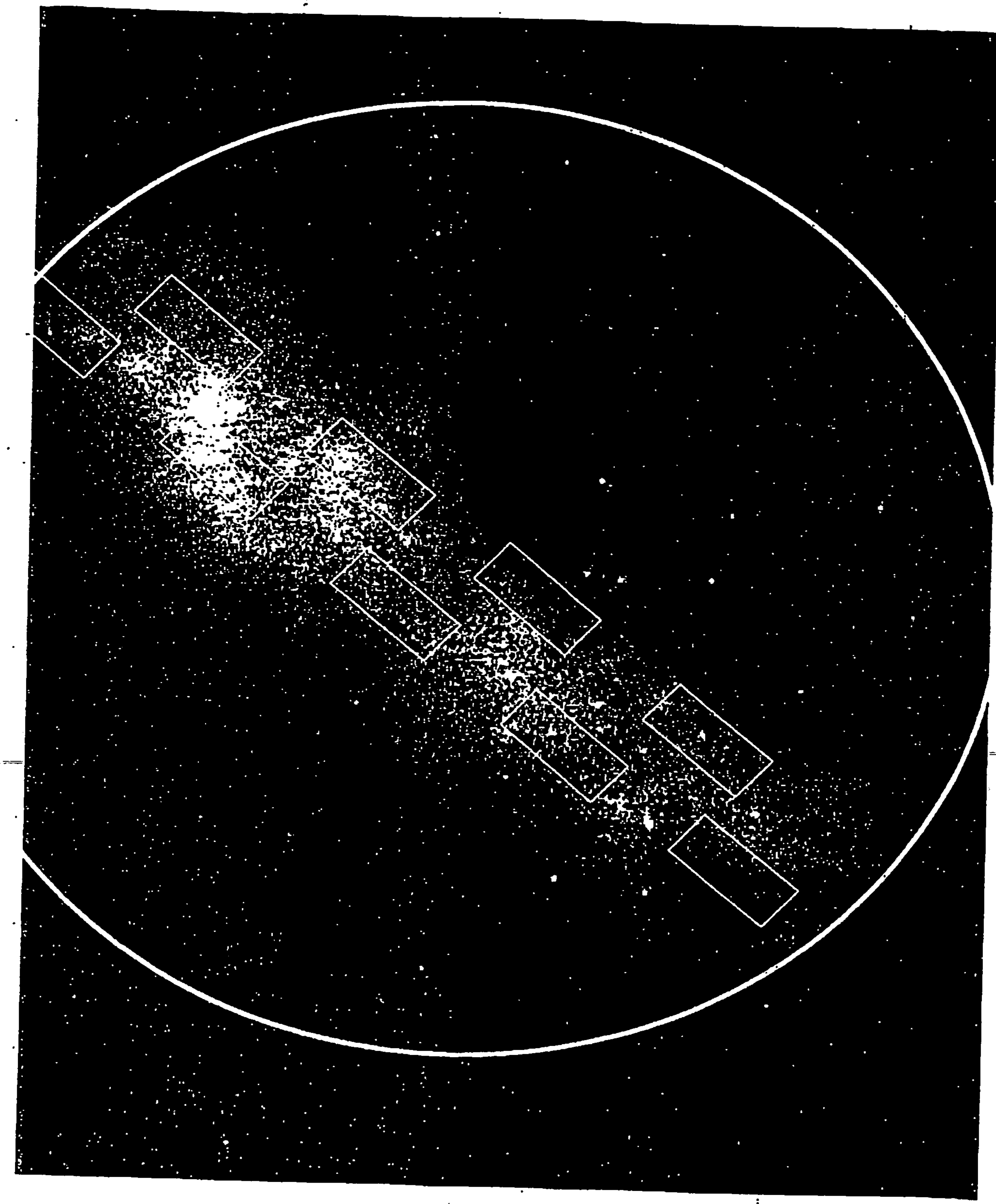
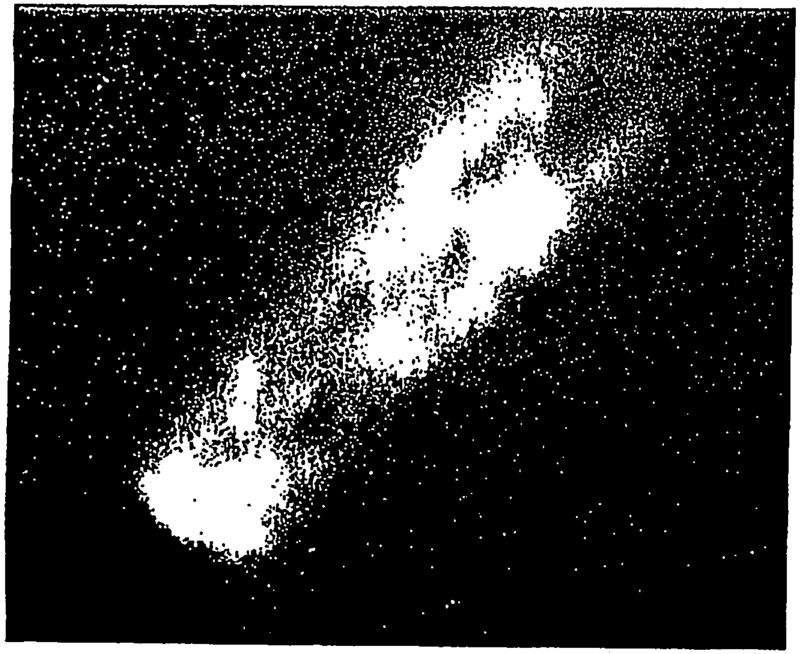


FIG.21P



All Transducers @ 5 V (Maximum output 75 fps.

FIG. 22A

FIG. 22B